NACA

RESEARCH MEMORANDUM

FREE-FLIGHT PERFORMANCE OF 16-INCH-DIAMETER SUPERSONIC RAM-JET UNITS

III - FOUR UNITS DESIGNED FOR COMBUSTION-CHAMBER-INLET MACH NUMBER OF 0.245 AT FREE-STREAM MACH NUMBER OF 1.8 (UNITS D-1, D-2, D-3, AND D-4)

By John H. Disher and Leonard Rabinowitz

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation of a series of 16-inch-diameter supersonic ram-jet units has been conducted in free flight. Supersonic flight speeds were obtained by releasing the units from an airplane at high altitude and allowing the engine thrust and the force of gravity to accelerate the unit. Data for evaluating the performance were obtained by use of radio-telemetering and radar-tracking equipment.

Performance data are presented for four individual ram-jet units over a range of free-stream Mach numbers from 0.49 to 1.78 and gas total-temperature ratios between 1.0 and 6.1. A maximum combustion efficiency of 88 percent was observed at a fuel-air ratio of 0.04 and combustion-chamber-inlet pressure, temperature, and velocity of 6000 pounds per square foot, 750° R, and 308 feet per second, respectively. Combustion blow-out was observed at the lean fuel-air ratios of 0.032 and 0.04 under some conditions, and rough explosive burning followed by rich blow-out was observed at fuel-air ratios of approximately 0.058 and 0.075 for one unit. At a free-stream Mach number of 1.70 and a gas total-temperature ratio of 4.0, a diffuser total-pressure recovery of approximately 0.89 was sustained; the corresponding thrust coefficient was approximately 0.79. The maximum net acceleration (excluding gravity) of 5.13 g's was attained at a free-stream Mach number of 1.77. The minimum external drag coefficient varied from approximately 0.10 at free-stream Mach numbers of 0.65 to 0.90 to approximately 0.36 at a free-stream Mach number of 1.23.

INTRODUCTION

The NACA Lewis laboratory is conducting a free-flight investigation of the performance of a series of 16-inch-diameter ram-jet units near the NACA Langley laboratory. The units are released from an airplane at high altitude and accelerated to supersonic velocities by the force of gravity and the engine thrust.

The investigation provides performance data at subsonic and supersonic velocities for a full-scale engine operating under actual flight conditions. Data are obtained at different values of fuel-air ratio by presetting the fuel regulator. Continuous data records are obtained by radio-telemetering and radar-tracking equipment throughout the flight.

In order to cover a range of combustion-chamber-inlet velocities, four ram-jet designs of varying inlet and outlet diameters (designated 16-A, 16-B, 16-C, and 16-D) are used. Data obtained with the first ram-jet unit investigated (16-A-1) are discussed in reference 1. Data for the succeeding four A-type units and five B-type units are presented in references 2 and 3, respectively. Data obtained with four D-type units are presented herein. Time histories of the performance are presented for altitudes from 35,000 feet to sea level and free-stream Mach numbers from 0.49 to 1.78. Effects of free-stream Mach number and gas total-temperature ratio on diffuser total-pressure recovery, thrust coefficient, and external drag coefficient are included as well as effects of fuel-air ratio and combustion-chamber-inlet pressure, temperature, and velocity on combustion efficiency and combustion stability.

A complete description of apparatus, instrumentation, procedure, and method of calculation is given in reference 2. A brief description of the four D-type units is presented herein.

APPARATUS

The four units investigated are designated 16-D-1, 16-D-2, 16-D-3, and 16-D-4. Model D was designed for a combustion-chamber-inlet velocity of 340 feet per second (Mach number 0.245) at a free-stream Mach number of 1.8 and a gas total-temperature ratio of 3.45. This heat addition would result from operation at a fuel-air ratio of 0.05 and a combustion efficiency of 60 percent at an altitude of 5000 feet. The diffuser is a single oblique-shock type with no internal contraction. The island dimensions are the same as for models A and B and the lip of the outer shell is located to

intercept the oblique shock at a free-stream Mach number of 1.80 with the normal shock at the inlet. One of the units installed on an airplane is shown in figure 1. A schematic cross-sectional diagram with dimensions for model D is shown in figure 2. Unit D-4
1294 was $8\frac{3}{8}$ inches longer than the other D units because the diffuser section was lengthened to provide additonal fuel-storage volume in the island.

The fuel system (fig. 3) utilizes helium stored under a pressure of approximately 3500 pounds per square inch to expel the fuel from a synthetic-rubber fuel cell with a capacity of $8\frac{1}{2}$ gallons for units D-1, D-2, and D-3, and 10 gallons for unit D-4. The fuel flow is controlled by regulating the helium pressure proportional to free-stream total pressure. Three spring-loaded reducing valves were used in the fuel system of units D-1 and D-2 and four reducing valves were used in units D-3 and D-4. The reducing valves open at successively higher pressures and each valve is connected to a separate set of fuel nozzles. This arrangement permits the use of high fuel pressures at low fuel-flow rates. The fuel used throughout the investigation was 73-octane gasoline (AN-F-23a).

A rake-type flame holder with seven magnesium flares (fig. 4) was used in all four units.

RESULTS AND DISCUSSION

A comparison of the free-stream Mach numbers attained by the four ram-jet units is shown in figure 5. The fuel cell for unit D-1 failed soon after release, and a terminal free-stream Mach number of only 0.79 was reached during the flight. Units D-2 and D-3, which were launched at approximately the same free-stream Mach number and altitude (0.50 and 28,000 ft), attained free-stream Mach numbers of 1.73 and 1.78 and maximum net accelerations (exclusive of gravity) of 3.7 and 5.13 g's, respectively. Unit D-4 was launched from an altitude of 35,000 feet at a free-stream Mach number of 0.54 and reached a maximum free-stream Mach number of 1.21.

Time histories of the performance of the ram-jet units are presented in figures 6 to 9. In general, these figures have been arranged in groups that describe resultant flight conditions, independent test variables, diffuser conditions, combustion-chamber-inlet variables, and performance variables. The dashed lines represent approximate values; such approximations were made wherever vibratory telemeter records prevented exact readings.

Units D-2 and D-3 encountered lean combustion stability limits, whereas rich stability limits were observed for unit D-4. Combustion blow-outs occurred under the following conditions:

Unit	Time after release (sec)	Fuel-air ratio, W_f/W_a	Combustion-chamber-inlet static pressure, p_4 (lb/sq ft)	Combustion-chamber-inlet static temperature, t_4 ($^{\circ}R$)	Combustion-chamber-inlet velocity, V_4 (ft/sec)
D-2	14.5	0.04	950	480	200
D-2	21.8	.041	1150	503	230
D-2	37.2	.032	6600	780	370
D-3	40.2	0.032	9400	805	350
D-4	41.1	0.058[a]	3000	625	320[a]
D-4	50.7	.075[a]	3800	650	---

[a]Approximate values

The final blow-out of unit D-2 at 37.2 seconds occurred at an altitude of 5600 feet; instantly the unit started to "tumble" in the air and the telemeter transmitter failed. No explosion was visible and apparently the tumbling was caused by failure of the stabilizing fins. The single blow-out of unit D-3 at 40.2 seconds occurred at an altitude of 900 feet. Photographic records indicated that this blow-out produced a detonation that caused destruction of the unit. In addition to the factors tabulated, the fuel distribution and the atomization would be expected to have a considerable effect on combustion stability, particularly at low combustion-chamber pressures and temperatures. The difference in fuel-nozzle arrangement with units D-2 and D-3 apparently contributed to differences in combustion stability at combustion-chamber pressures below approximately 1500 pounds per square foot. Unit D-3 operated at fuel-air ratios as low as 0.02 at these combustion-chamber pressures, although with very low efficiency (fig. 8(d)); whereas unit D-2 blew out at fuel-air ratios of 0.04 and 0.041 and combustion-chamber pressures of 950 and 1150 pounds per square foot (figs. 7(d), 7(e), and preceding table). A comparison of the combustion efficiency and the primary variables affecting efficiency for units D-2 and D-3 is shown in figure 10. Combustion-chamber pressure was chosen for the abscissa because this quantity had the greatest variation during the flights. Peak combustion efficiencies of 88 and 78 percent were observed for units D-2 and D-3, respectively, at a fuel-air ratio of 0.04 and

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combustion-chamber-inlet pressures, temperatures, and velocities of 6000 and 8800 pounds per square foot, 750° and 780° R, and 308 and 306 feet per second, respectively.

In order to determine the performance of the D unit at higher fuel-air ratios, the fuel system of the unit D-4 was set to provide higher fuel flow than units D-1, D-2, and D-3, and the fuel tank was enlarged to a capacity of 10 gallons. The launching altitude of 35,000 feet provided such low combustion-chamber pressures and temperatures (approximately 500 lb/sq ft and 425° R) that combustion was not sustained during the first 29 seconds after release even though a fuel-air ratio of approximately 0.05 to 0.042 was maintained (figs. 9(d) and 9(e)). At 29 seconds when a combustion-chamber-inlet pressure of 1100 pounds per square foot was reached, ignition occurred. Smooth, steady combustion occurred until 39.8 seconds, when a low amplitude vibration of approximately 50 cycles per second started; the amplitude of vibration increased until approximately 41.1 seconds when blow-out occurred. The fuel-air ratio was approximately 0.058 during this period. A photographic record of this transition from steady burning to blow-out is shown in figure 11. During the deceleration that followed, the fuel-air mixture started to burn outside the unit and continued to burn outside until 48.2 seconds, when the combustion-chamber-inlet velocity had decreased to a value that allowed efficent combustion to resume. The resulting increase in heat addition changed the fuel-air ratio to approximately 0.075 and rough explosive burning of approximately 50 cycles per second started, as shown in the photographs covering 48.3 to 50.5 seconds. At approximately 50.6 seconds, blow-out reoccurred and the unit decelerated until impact. The rich instability and blow-out occurred at fuel-air ratios of 0.058 and 0.075 with corresponding pressures of 3000 and 3800 pounds per square foot and temperatures of 625° and 650° R, respectively. The blow-out of unit D-4 at 41.1 seconds occurred at combustion-chamber-inlet conditions under which units D-2 and D-3 had burned satisfactorily. This blow-out at a fuel-air ratio of 0.058 was apparently caused by the opening of the third set of fuel nozzles at 40 seconds, which produced a temporary local enrichment (fig. 9(b)).

The total-pressure recovery across the diffuser is shown to decrease at a constant-free-stream Mach number with a decrease in heat addition in figure 12. The lines of constant total-temperature ratio were faired from data points for the four units considered herein. For example, at a free-stream Mach number of 1.2, the diffuser total-pressure recovery decreased from approximately 0.92 to 0.69 with a decrease in gas total-temperature from 4.0 to 1.2.

The lower values of heat addition resulted in diffuser-outlet conditions of higher velocity, lower static pressure, and a reduction in total pressure necessary for mass continuity. When sonic or supersonic velocity existed at the diffuser inlet, this reduction in total pressure was made possible only by the presence of a normal shock within the diffuser with its accompanying total-pressure loss. With a gas total-temperature ratio of 1.0, the transition from internal subsonic flow to internal supersonic flow occurred at a free-stream Mach number of approximately 0.65; whereas a gas total-temperature ratio of 4.0 maintained internal subsonic flow at free-stream Mach numbers up to 1.70 and would continue to do so up to a free-stream Mach number of approximately 1.9. The diffuser total-pressure recovery was 0.89 at a gas total-temperature ratio of 4.0 and a free-stream Mach number of 1.70; thus only a 3-percent loss in pressure recovery was sustained when the Mach number was increased from 1.2 to 1.7 at a gas total-temperature ratio of 4.0 1294

The variation in net-thrust coefficient (defined as the total change in momentum of fuel and air flowing through the ram jet divided by the maximum cross-sectional area and the free-stream dynamic pressure) with free-stream Mach number and gas total-temperature ratio is shown in figure 13. A maximum thrust coefficient of 0.88 observed for the four units occurred at a free-stream Mach number of 1.5 and a gas total-temperature ratio of 4.6. At a gas total-temperature ratio of 4.0, the thrust coefficient increased from approximately 0.26 to 0.79 when the Mach number increased from 0.7 to 1.70.

The variation of external drag coefficient with free-stream Mach number and gas total-temperature ratio is shown in figure 14. The external drag has been defined as the total change in momentum of the air flowing outside the ram-jet unit and therefore includes the additive drag at the diffuser inlet as well as the total external drag on the shell and the fins. Thus a heat addition sufficient to alter the external-flow conditions forward of the diffuser inlet would change the external drag coefficient because of the effect on additive drag. A line has been drawn through the data that are believed to represent minimum drag. This minimum drag would result from heat additions at or below a critical value that would allow the maximum possible air flow through the unit. This critical heat addition would vary from a gas total-temperature ratio of 1.0 at a free-stream Mach number of approximately 0.65 to a gas total-temperature ratio of 3.45 at a free-stream Mach number of 1.8. The minimum drag coefficient increased from approximately 0.10 at subsonic Mach numbers to a peak value of approximately 0.36 at a Mach number of 1.23. At Mach numbers of 1.73 and 1.77, minimum drag coefficients of approximately 0.23 were observed with a heat addition less than critical. A maximum drag coefficient of 0.40 was observed at a Mach number of 1.26 with a gas total-temperature ratio of 4.7.

SUMMARY OF RESULTS

From the data obtained during free-flight investigations of four 16-inch-diameter supersonic ram-jet units over a range of free-stream Mach numbers from 0.49 to 1.78, combustion-chamber-inlet Mach numbers of 0.11 to 0.36, and gas total-temperature ratios between 1.0 and 6.1, the following results were observed:

1. Lean combustion instability and blow-out were encountered with two of the units. Blow-out of unit D-2 occurred at fuel-air ratios of 0.04 and 0.032 with combustion-chamber-inlet pressures and temperatures of 950 and 6600 pounds per square foot and 480° and 780° R, respectively. Blow-out of unit D-3 occurred at a fuel-air ratio of 0.032 and combustion-chamber inlet pressure and temperature of 9400 pounds per square foot and 805° R, respectively.

2. Rich combustion instability and blow-out were encountered with unit D-4 at fuel-air ratios of approximately 0.058 and 0.075, with combustion-chamber-inlet pressures and temperatures of 3000 and 3800 pounds per square foot and 625° and 650° R, respectively.

3. Peak combustion efficiencies of 88 and 78 percent were observed for units D-2 and D-3, respectively, at a fuel-air ratio of 0.04 and combustion-chamber-inlet pressures, temperatures, and velocities of 6000 and 8800 pounds per square foot, 750° and 780° R, 308 and 306 feet per second, respectively.

4. At a free-stream Mach number of 1.2, the diffuser total-pressure recovery decreases from approximately 0.92 to 0.69 with a decrease in gas-total temperature ratio from 4.0 to 1.2. At a free-stream Mach number of approximately 1.7 and a gas total-temperature ratio of 4.0, the diffuser total-pressure recovery was 0.89.

5. At a gas total-temperature ratio of 4.0, the thrust coefficient increased from 0.26 to 0.79 when the Mach number increased from 0.70 to 1.70. The maximum thrust coefficient of 0.88 was observed at a free-stream Mach number of 1.5 and a gas total-temperature ratio of 4.6. The maximum net acceleration (excluding gravity) attained was 5.13 g's at a Mach number of 1.77.

6. The average minimum values of external drag coefficient varied from approximately 0.10 at free-stream Mach numbers of 0.65 to 0.90 to approximately 0.36 at a free-stream Mach number of 1.23. Near design conditions at a free-stream Mach number of 1.77, a minimum drag coefficient of approximately 0.23 was observed.

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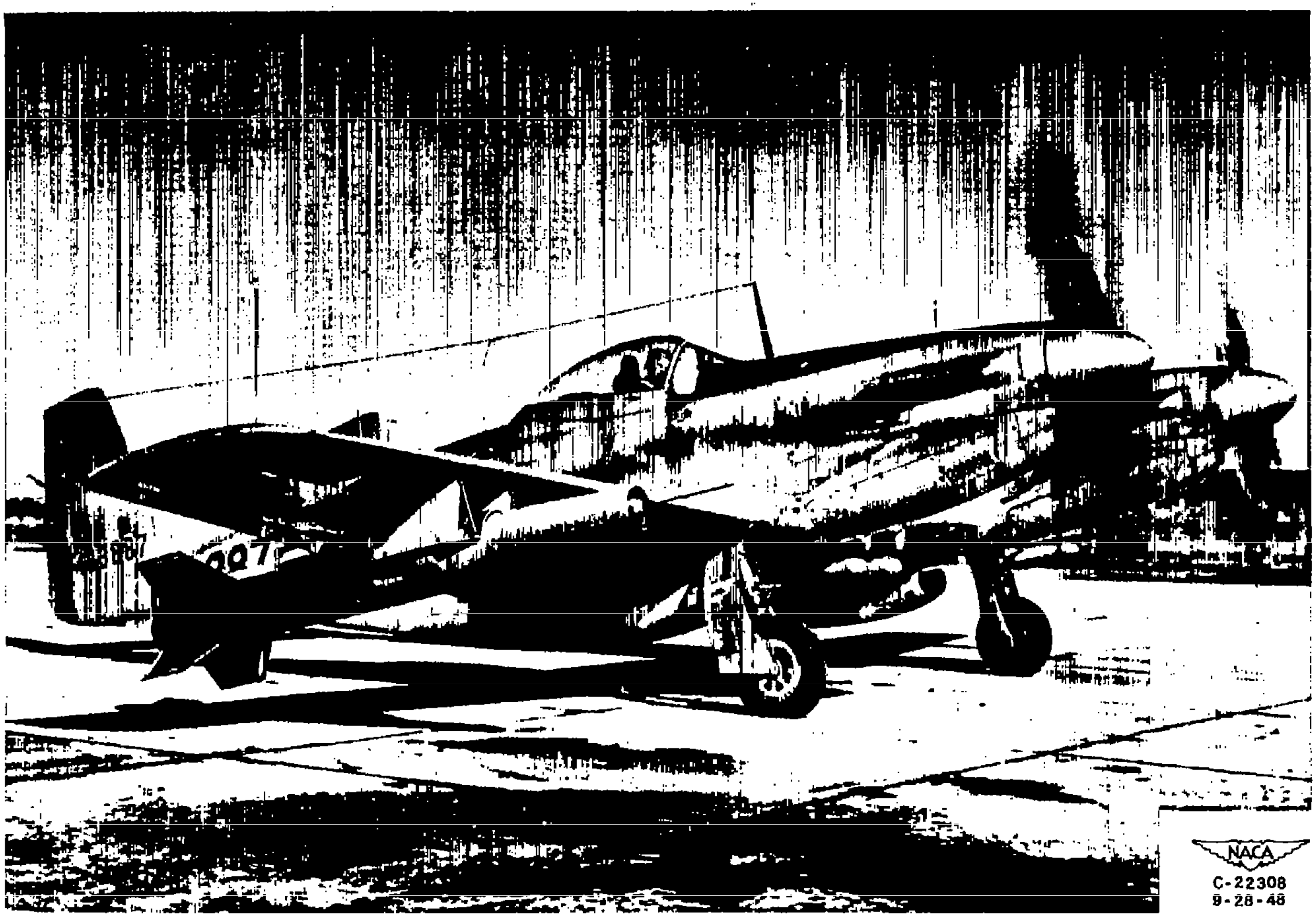

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Figure 1. - Supersonic 16-inch ram-jet unit mounted beneath airplane wing.

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Model	Dimension, in. A	B
D-1,2,3	190.25	85.89
D-4	198.63	94.27

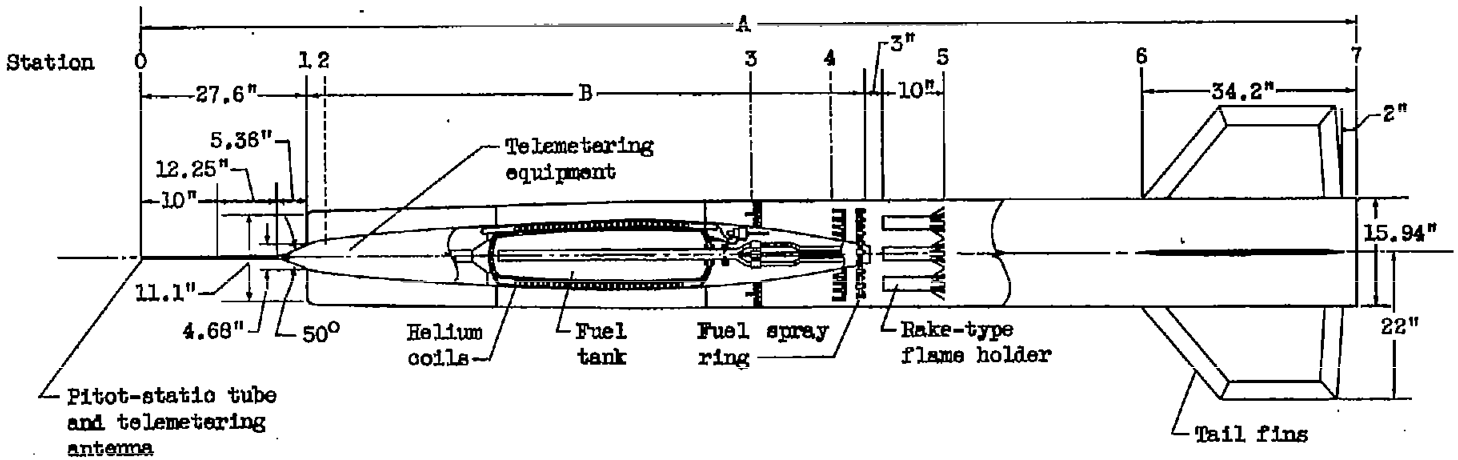

Figure 2. - Schematic cross-sectional diagram of supersonic 16-inch-diameter ram-jet unit; dimensions given for units D-1, D-2, D-3, and D-4.

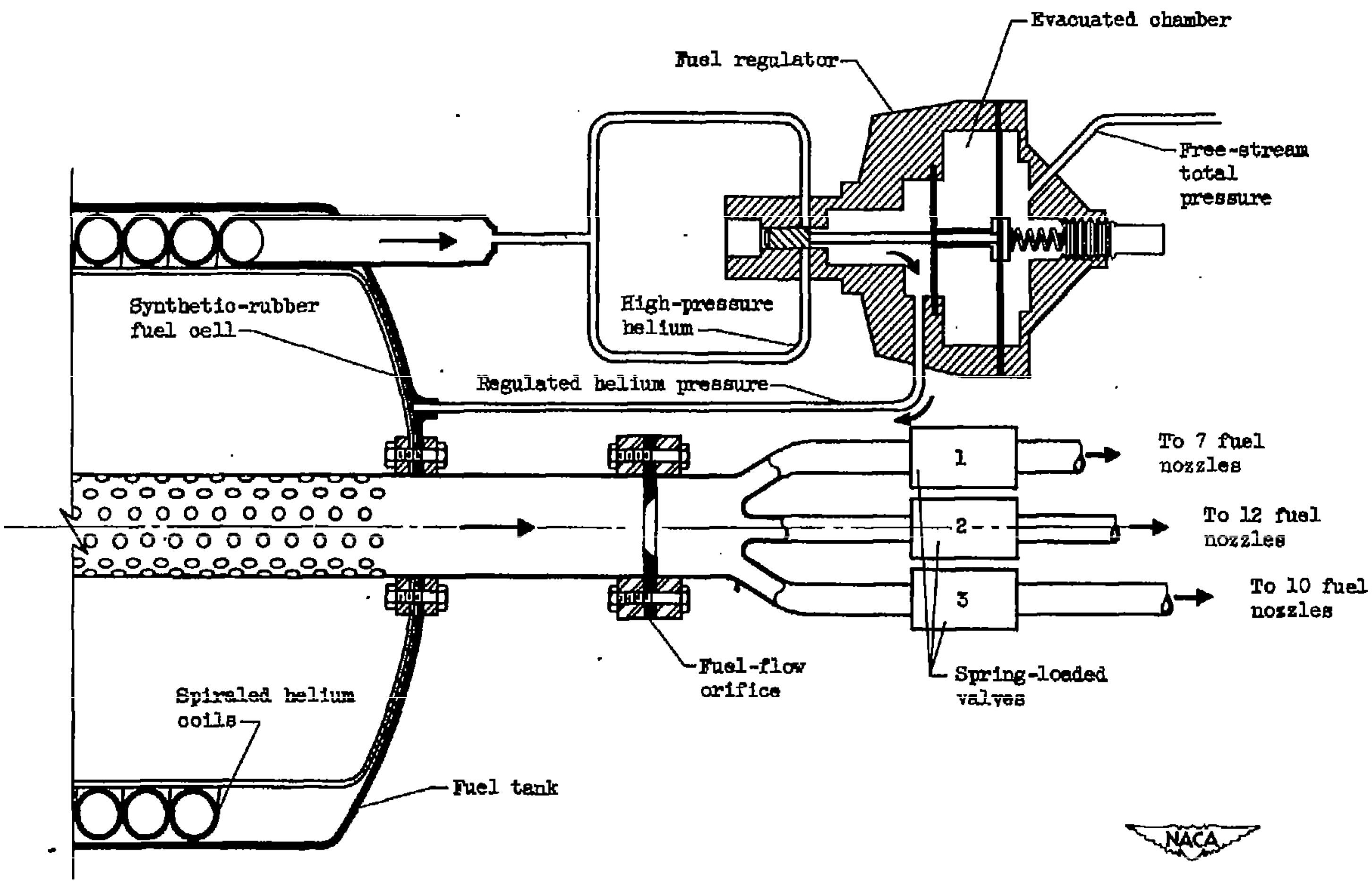

Figure 3. - Schematic diagram of fuel system for supersonic 16-inch ram-jet units 16-D-1 and 16-D-2. (Units 16-D-3 and 16-D-4 had a fourth spring-loaded valve connected to three nozzles.)

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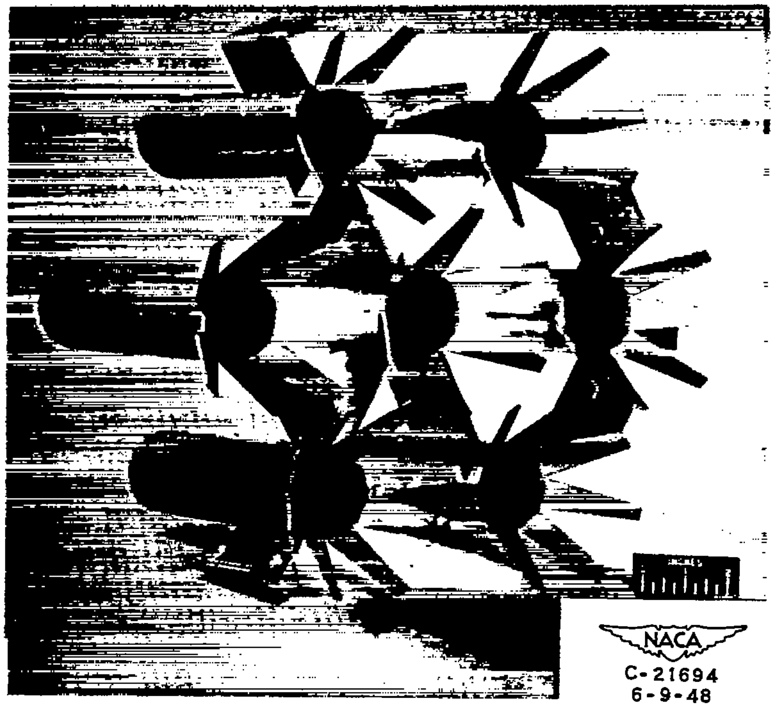

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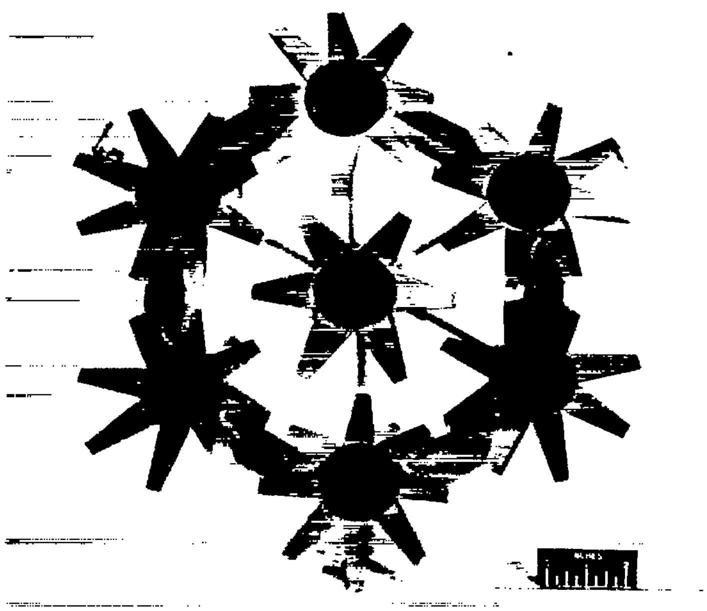
(a) Three-quarter rear view.



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(b) Rear view.

Figure 4. - Flame holder for supersonic 16-inch ram-jet units 16-D-1, 16-D-2, 16-D-3, and 16-D-4.

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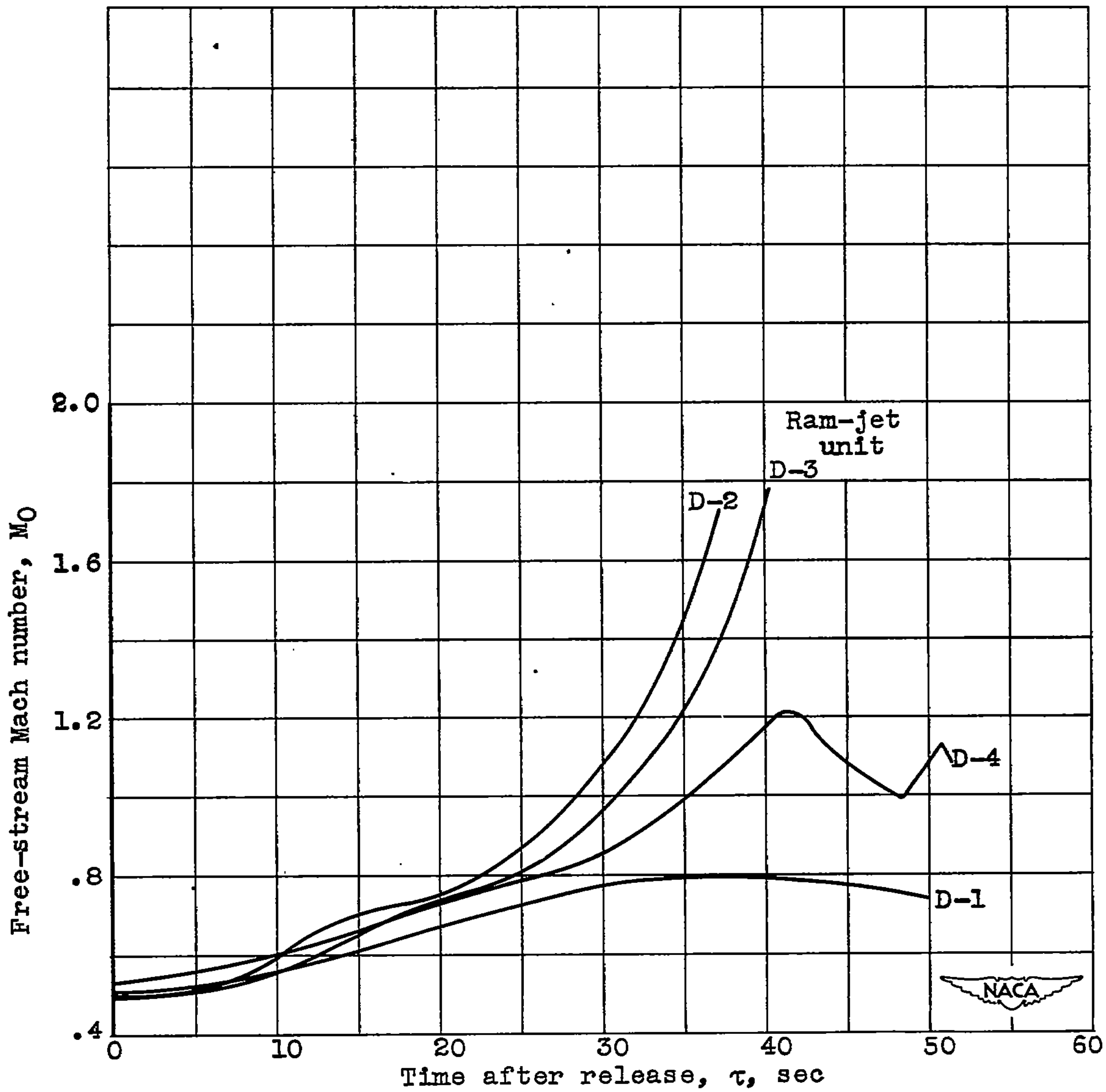

Figure 5. - Comparison of free-stream Mach numbers for ram-jet units 16-D-1, 16-D-2, 16-D-3, and 16-D-4.

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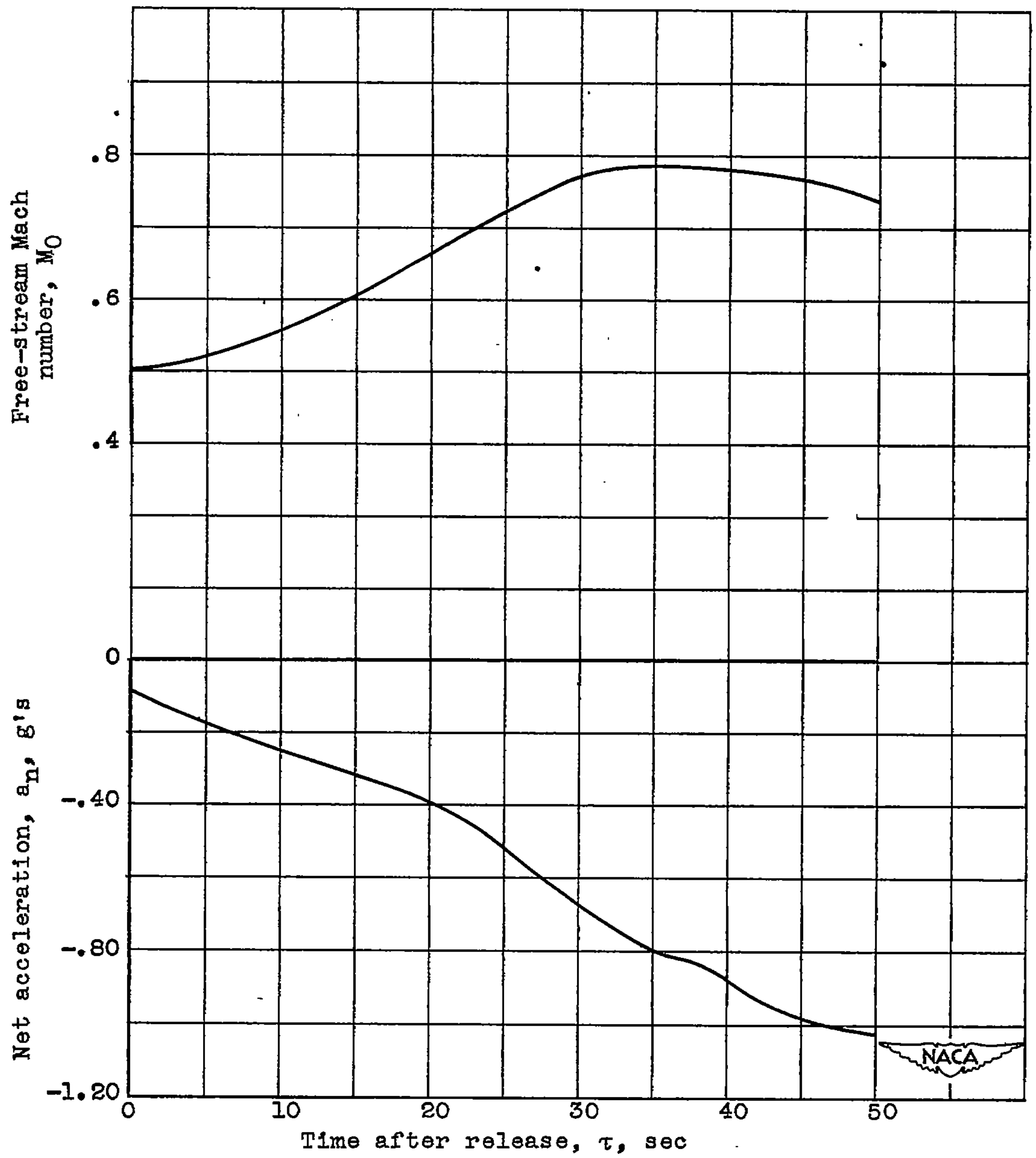

(a) Resultant flight conditions.

Figure 6. - Time history of flight data and performance of ram-jet unit 16-D-1.

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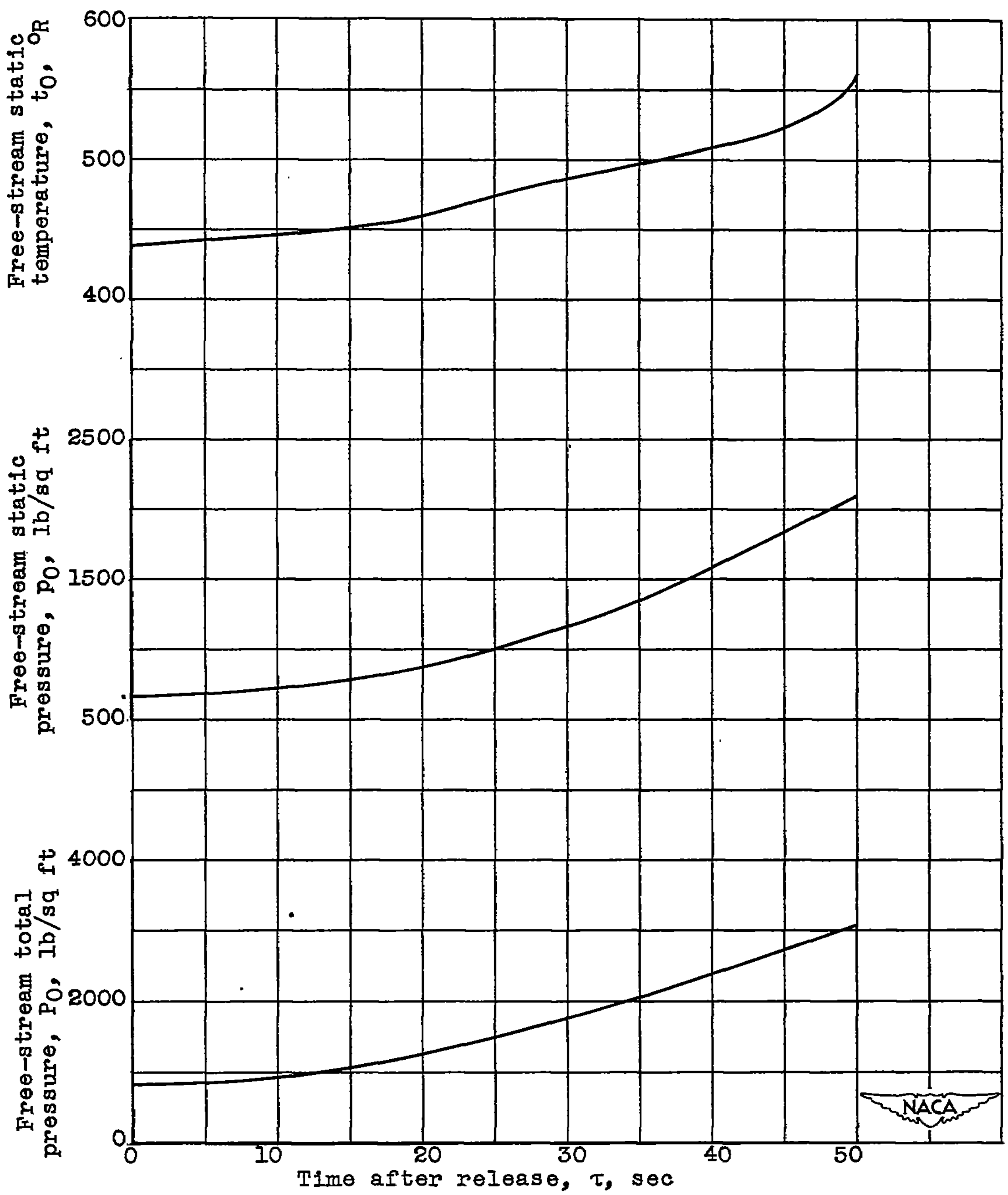

(b) Independent test variables.

Figure 6. - Continued. Time history of flight data and performance of ram-jet unit 16-D-1.

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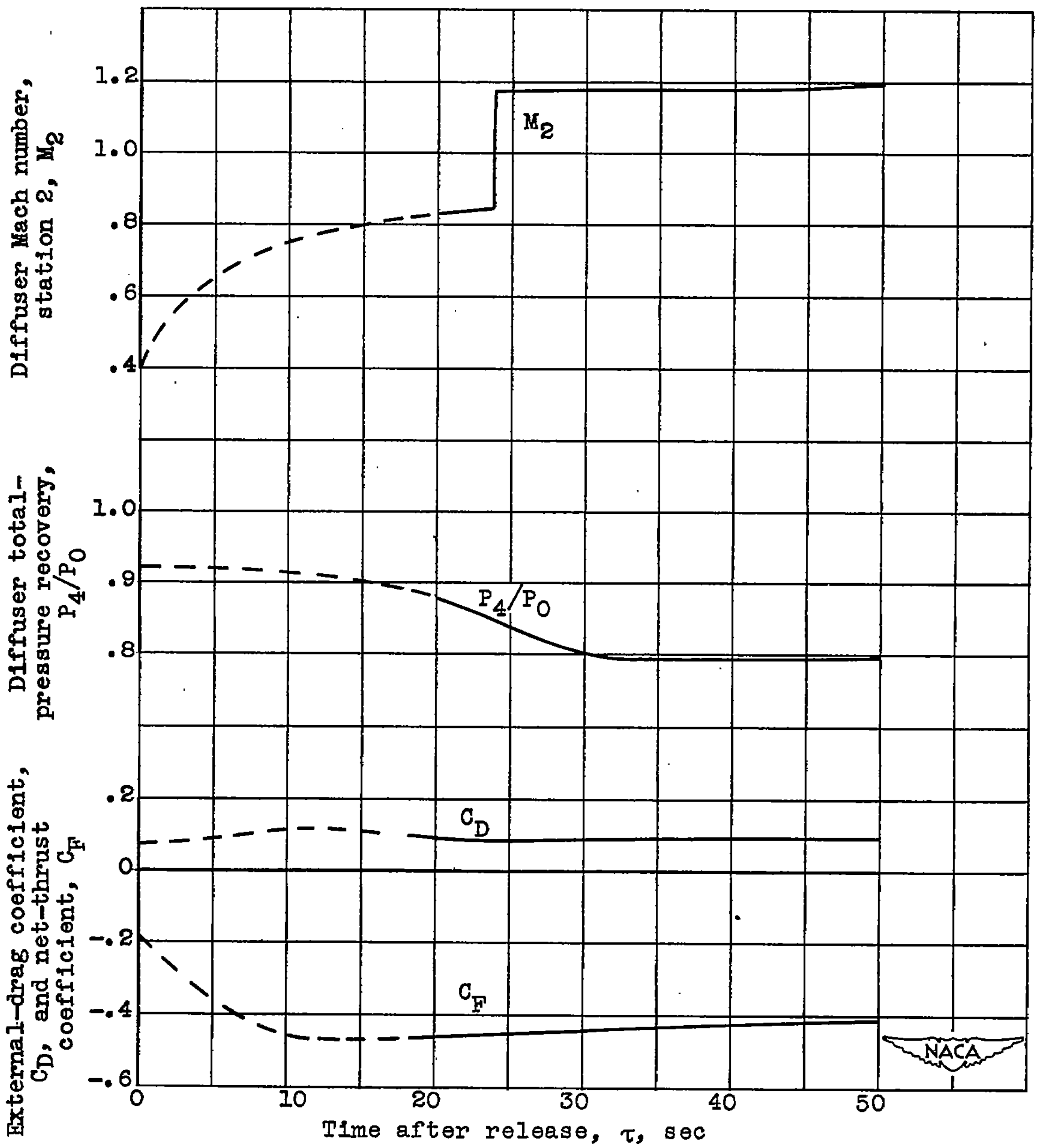
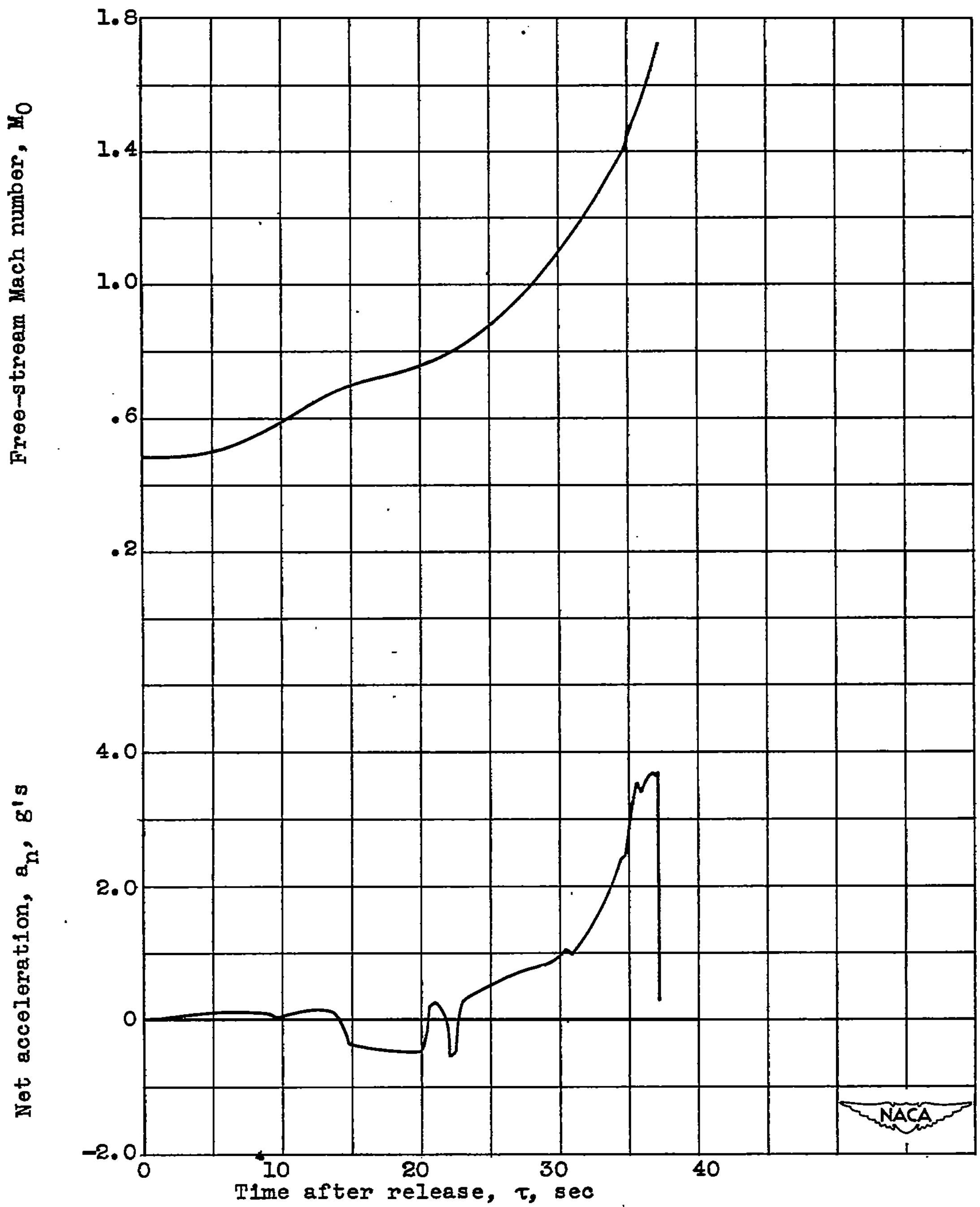


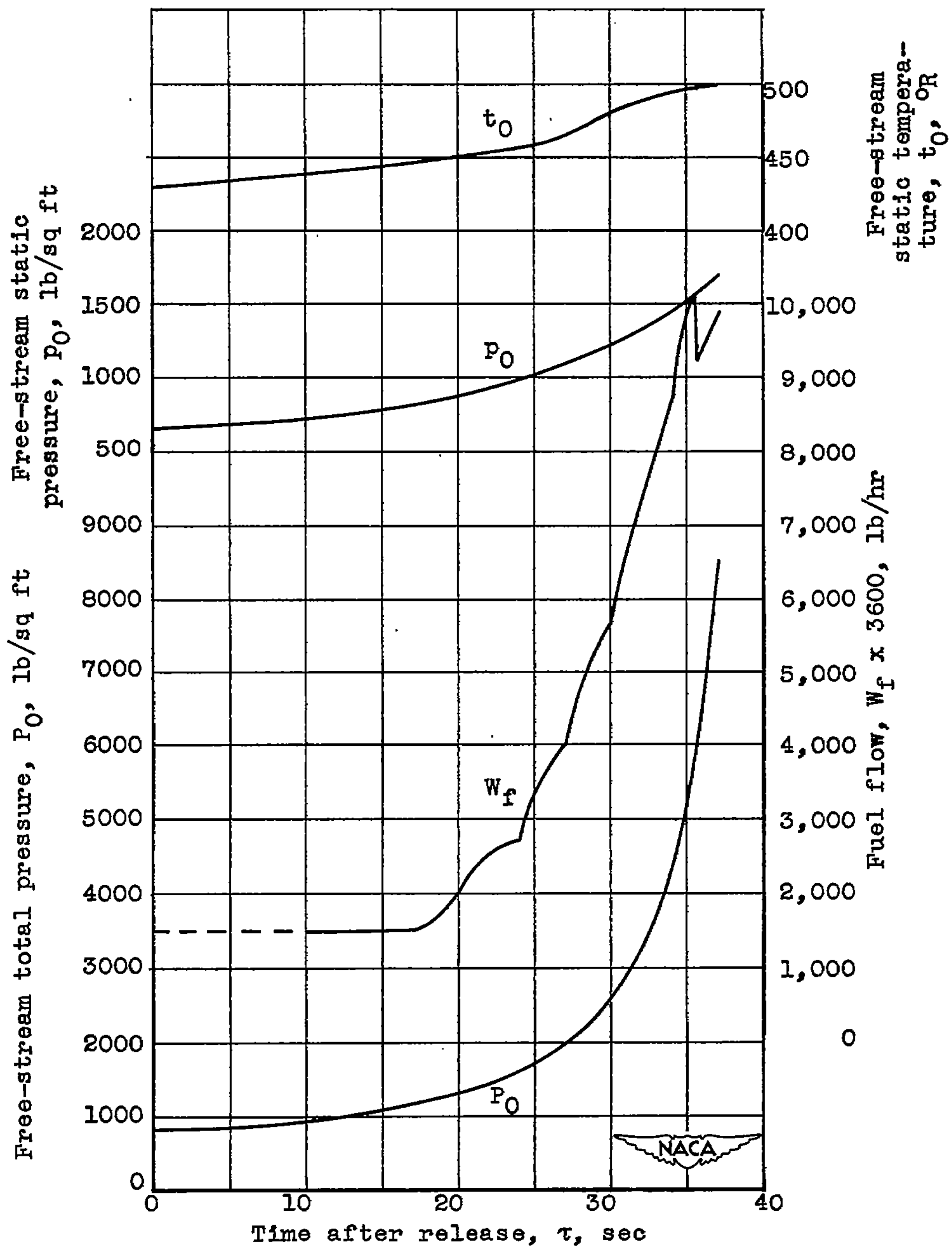
(c) Diffuser conditions and external-drag and net thrust coefficients.

Figure 6. - Concluded. Time history of flight data and performance of ram-jet unit 16-D-1.



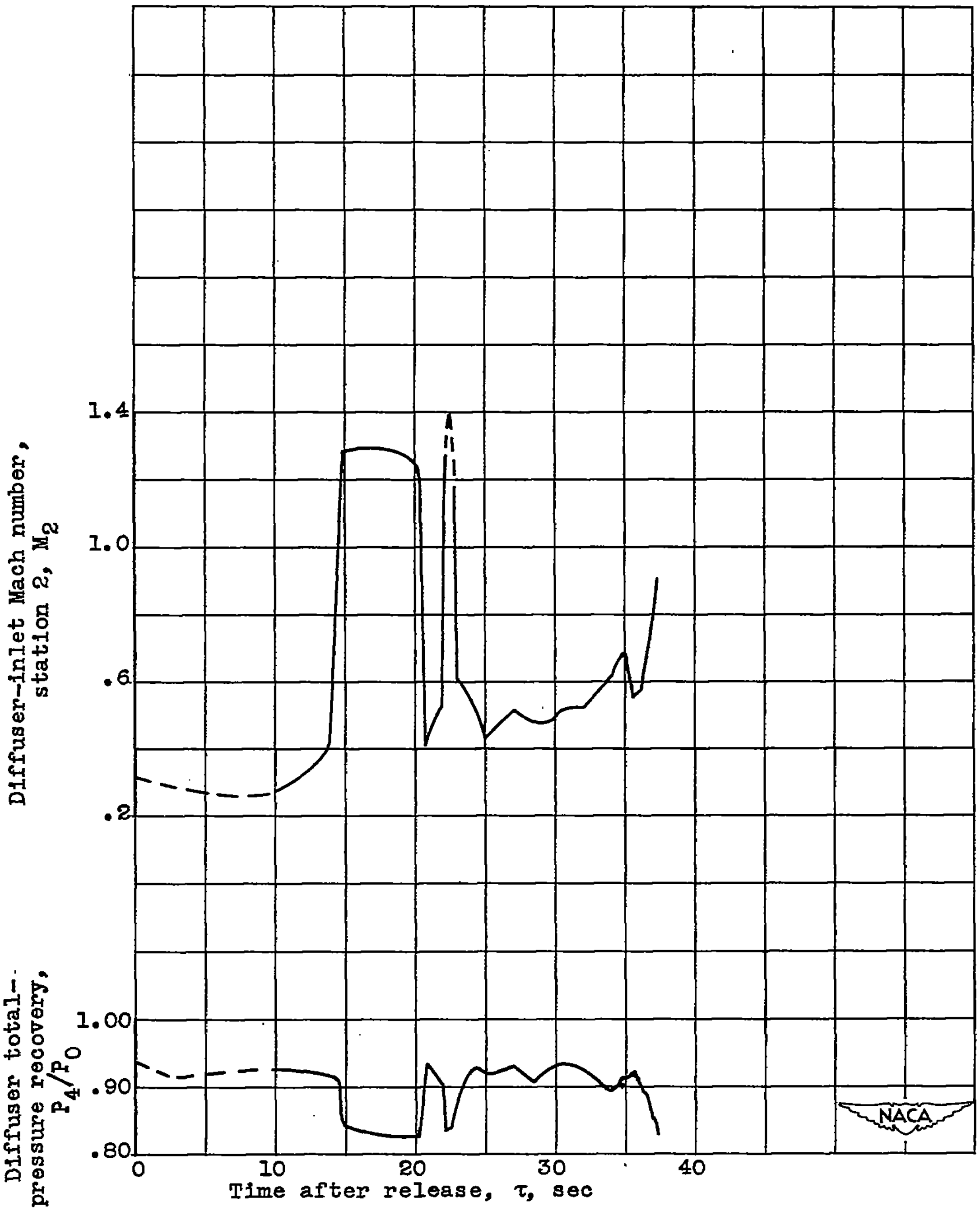
(a) Resultant flight conditions.

Figure 7. - Time history of flight data and performance of ram-jet unit 16-D-2.



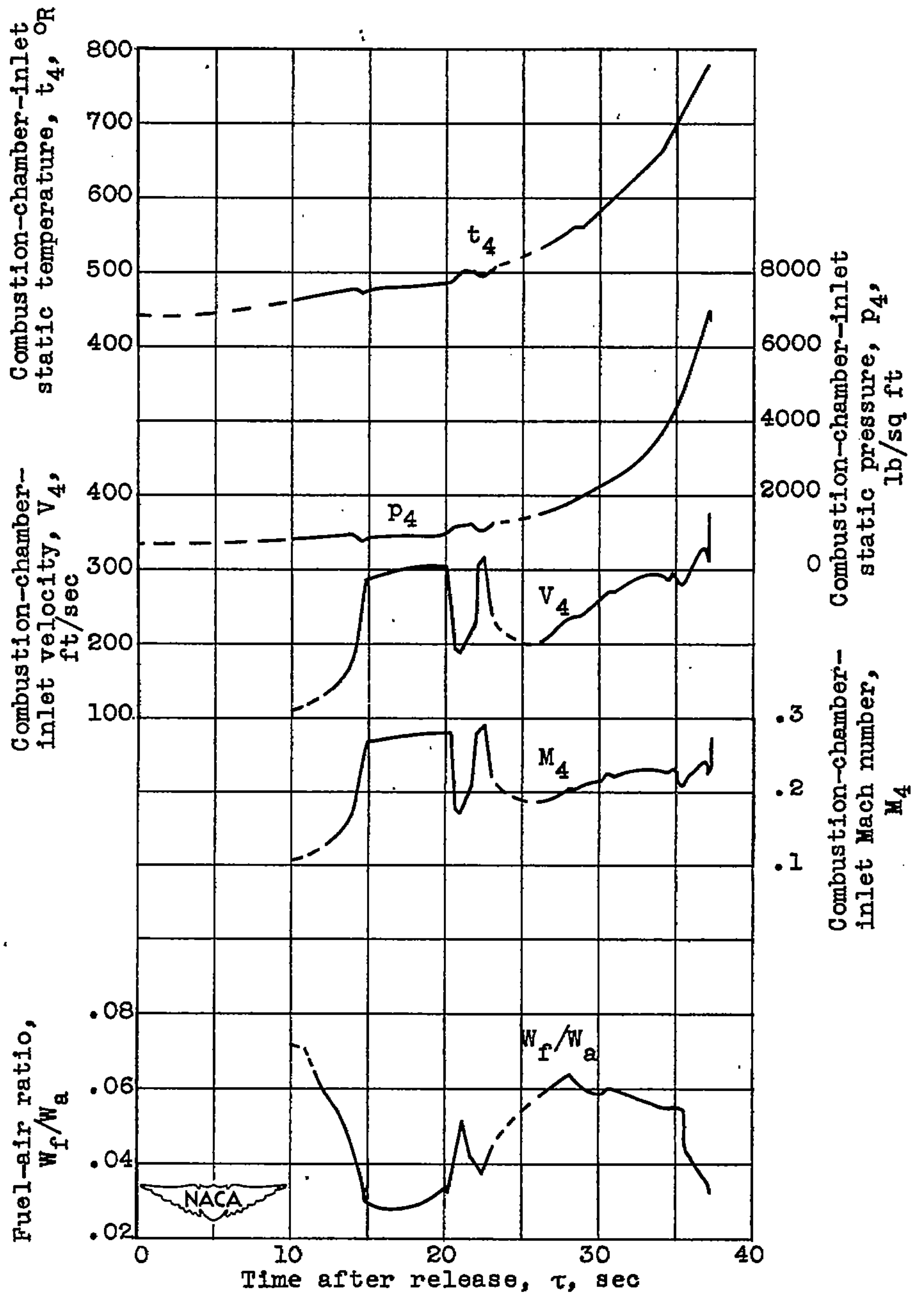
(b) Independent test variables.

Figure 7. - Continued. Time history of flight data and performance of ram-jet unit 16-D-2.



(c) Diffuser variables.

Figure 7. - Continued. Time history of flight data and performance of ram-jet unit 16-D-2.



(d) Combustion-chamber-inlet variables.

Figure 7. - Continued. Time history of flight data and performance of ram-jet unit 16-D-2.

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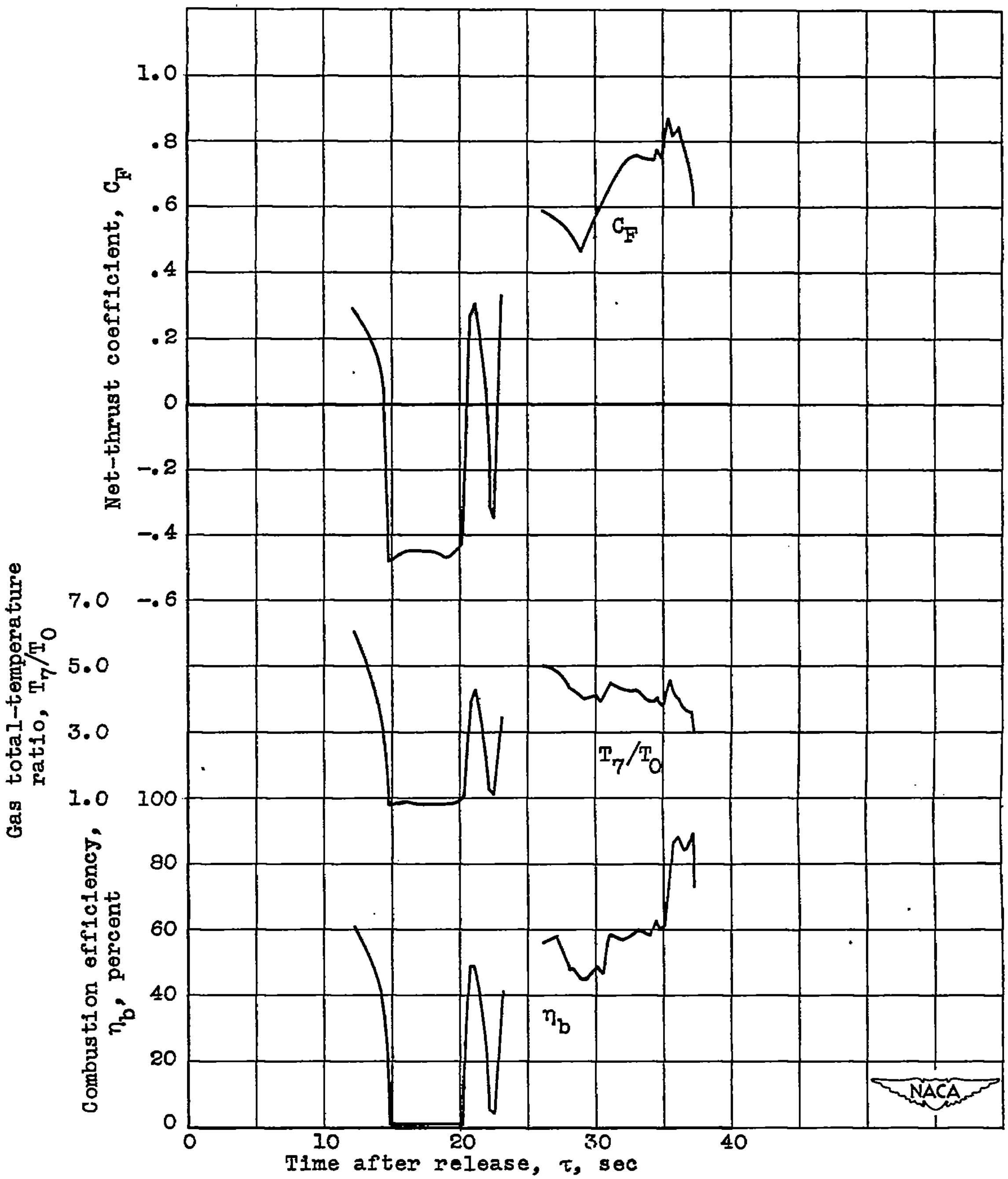

(e) Performance variables.

Figure 7. - Continued. Time history of flight data and performance of ram-jet unit 16-D-2.

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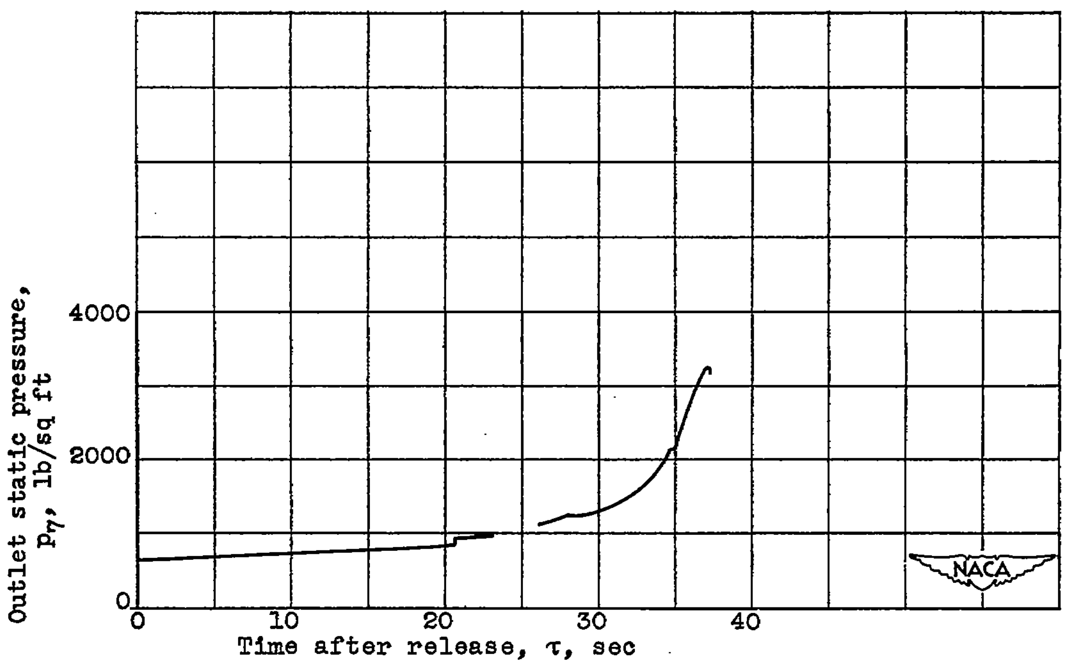

(e) Concluded. Performance variables.

Figure 7. - Concluded. Time history of flight data and performance of ram-jet unit 16-D-2.

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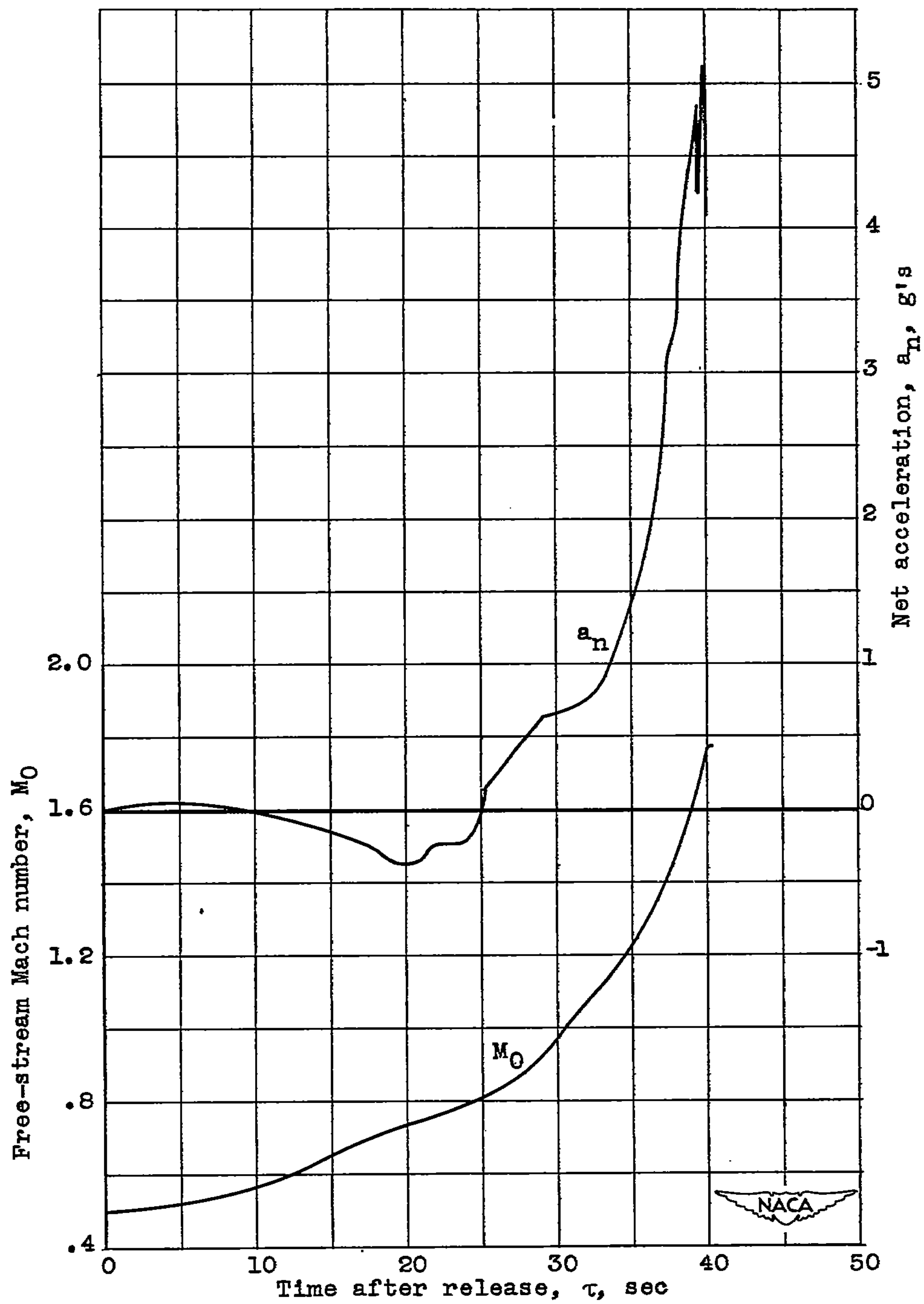
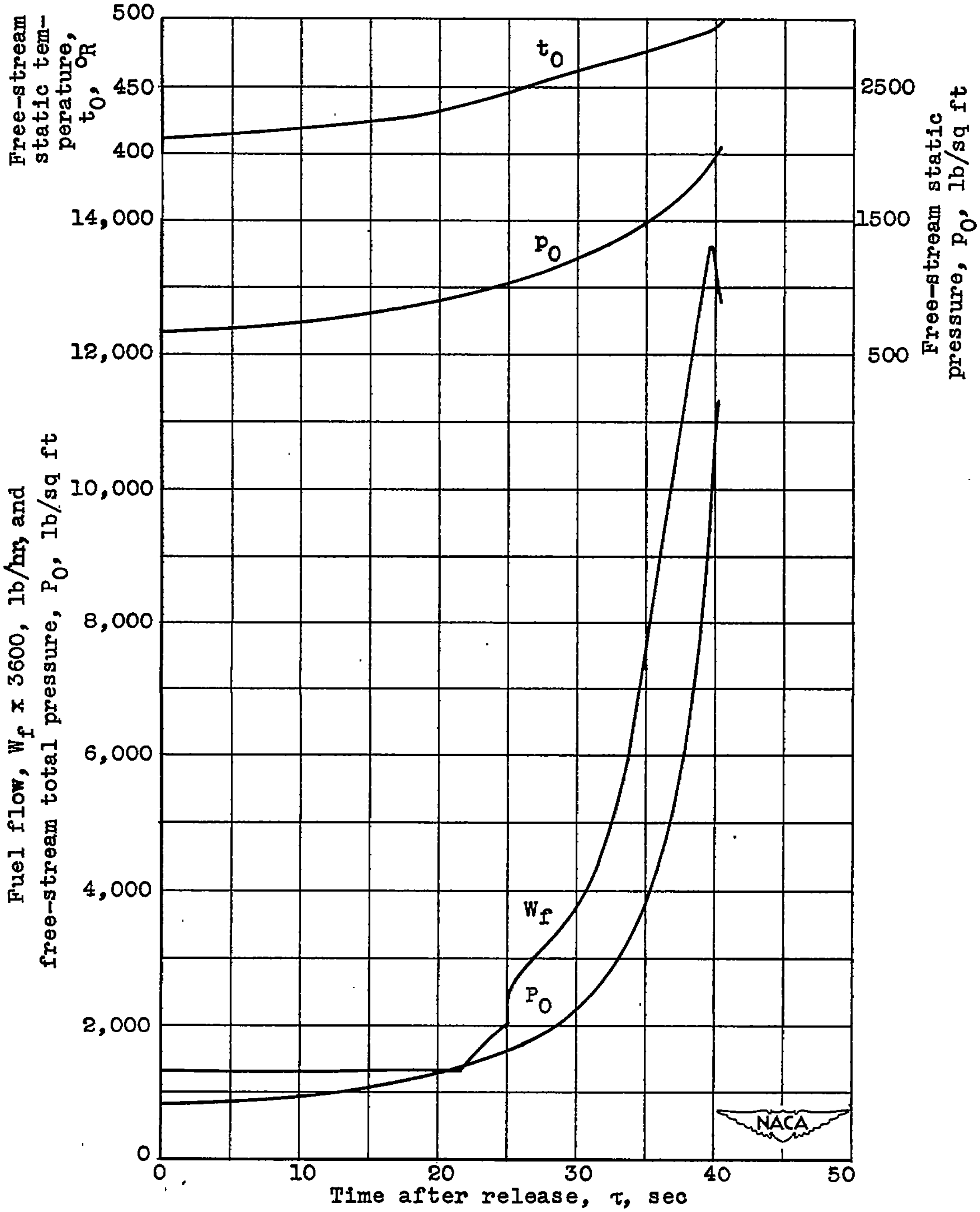


(a) Resultant flight conditions.

Figure 8. - Time history of flight data and performance of ram-jet unit 16-D-3.



(b) Independent test variables.

Figure 8. - Continued. Time history of flight data and performance of ram-jet unit 16-D-3.

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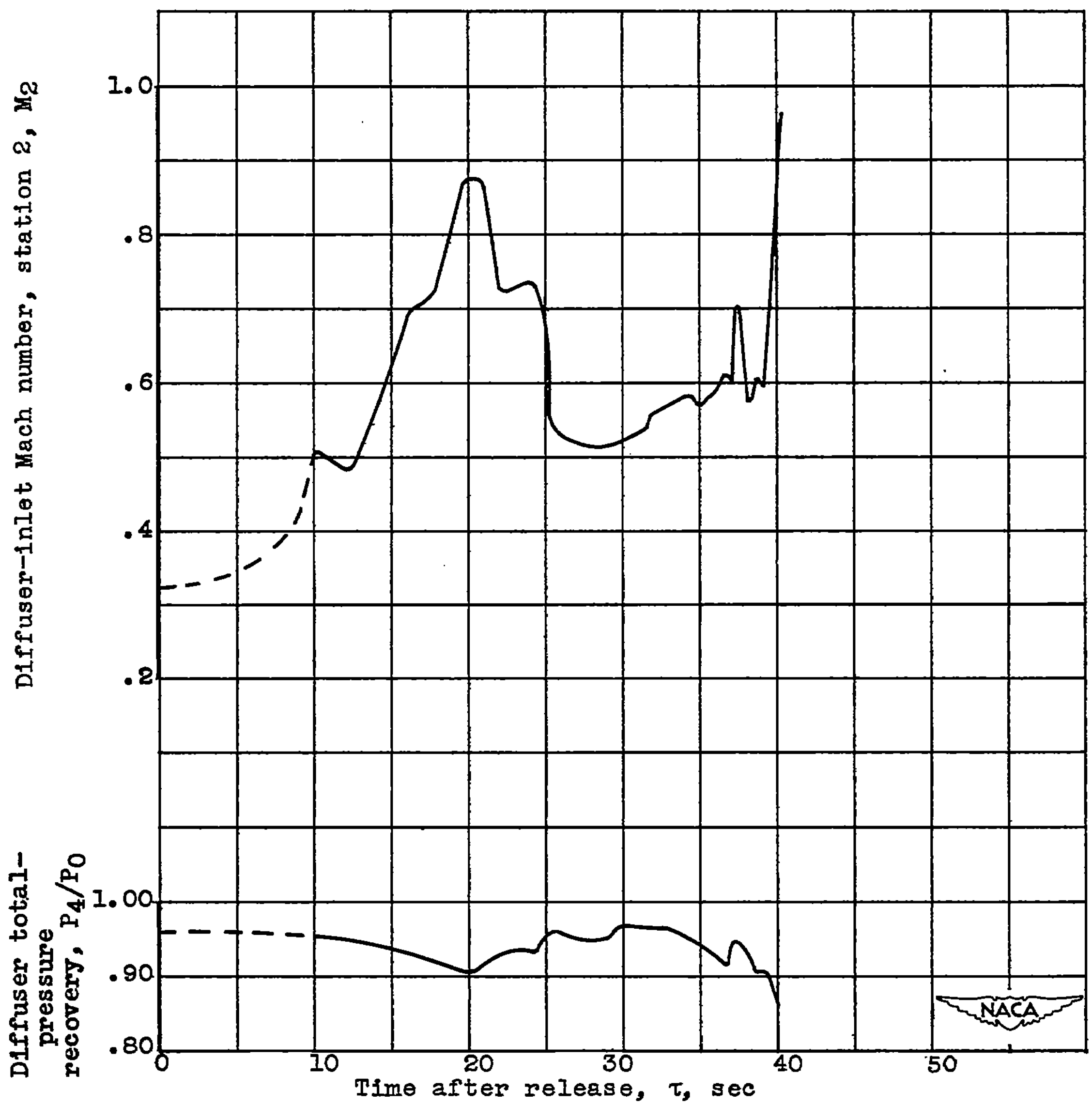
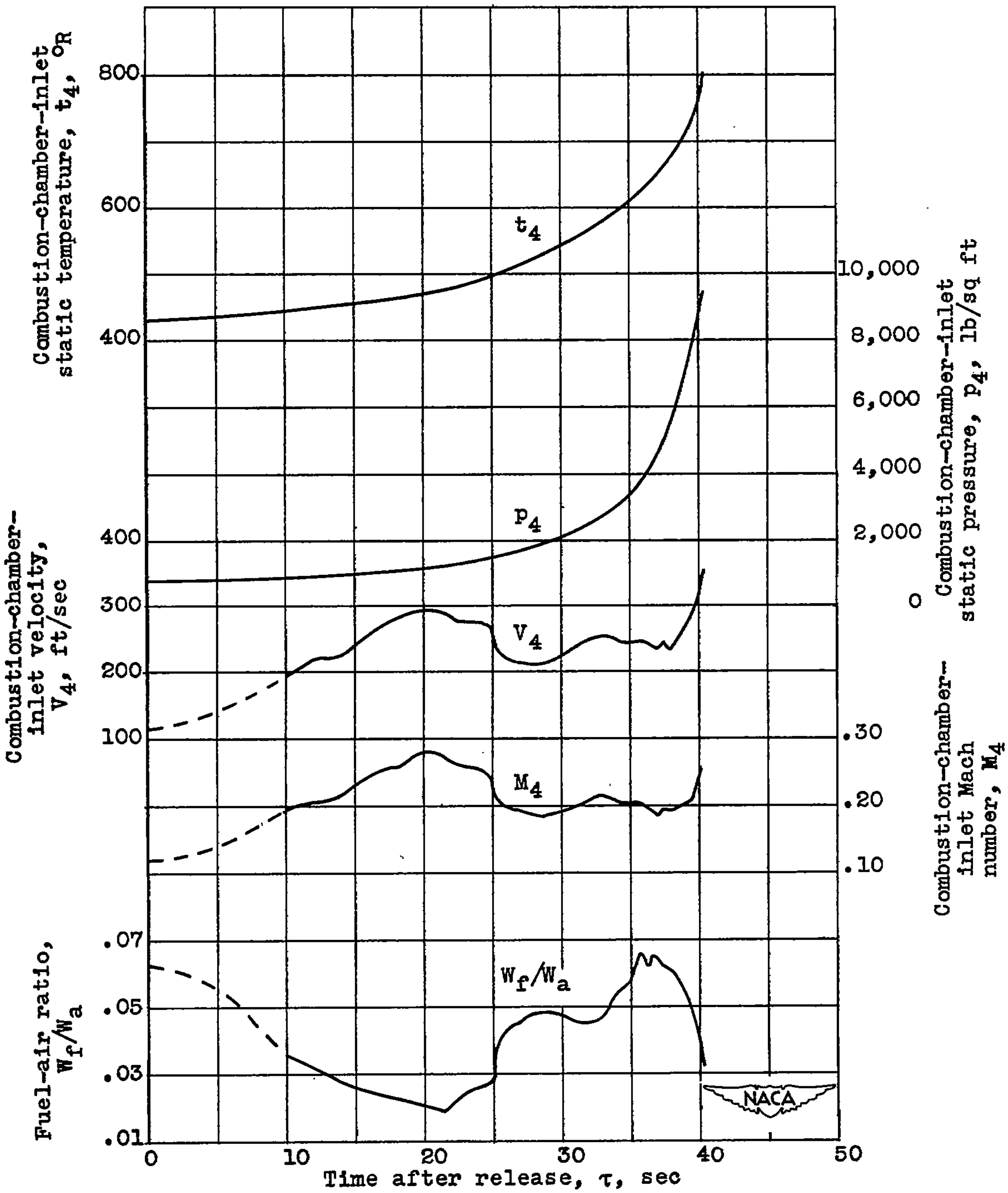


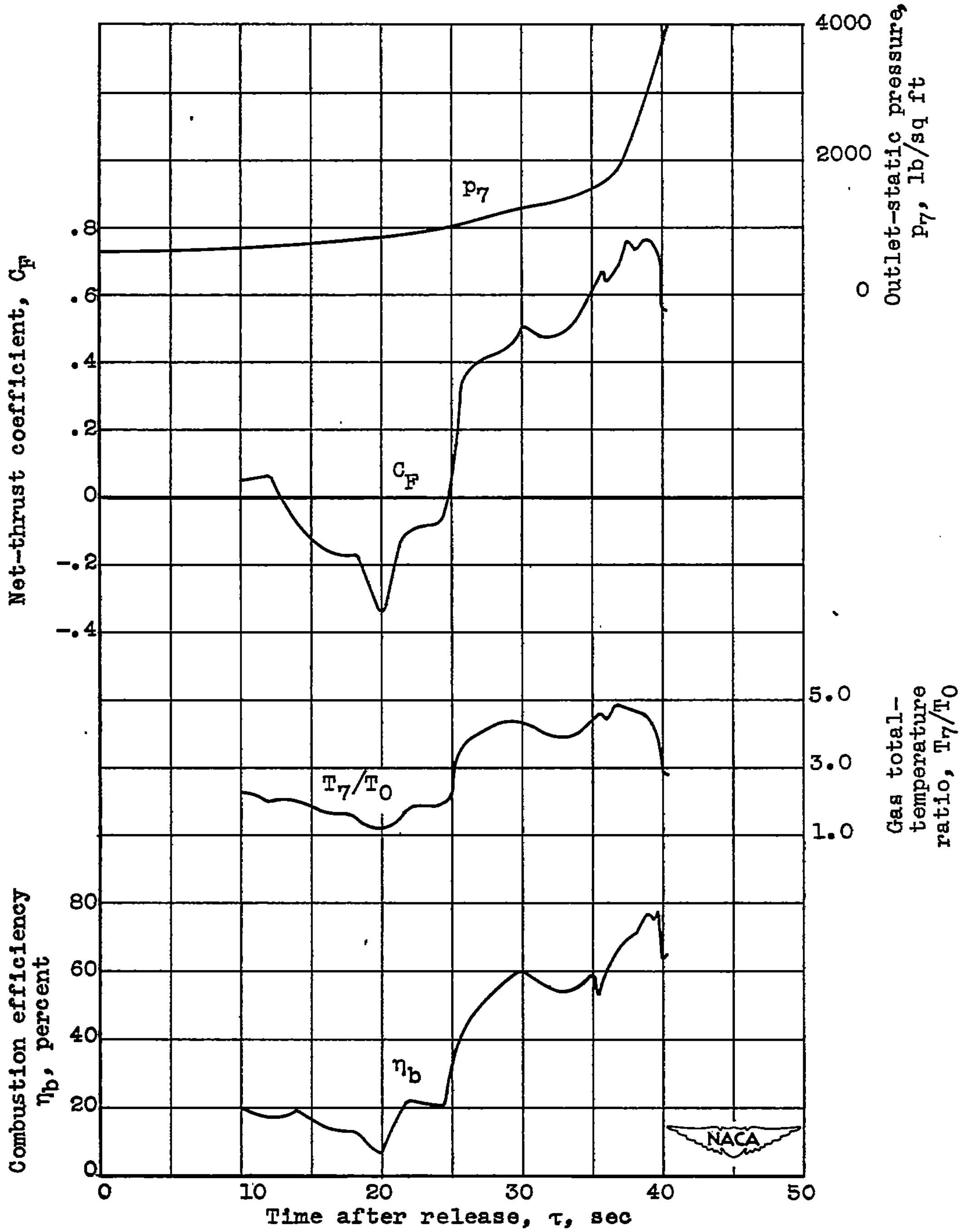
(c) Diffuser variables.

Figure 8. - Continued. Time history of flight data and performance of ram-jet unit 16-D-3.



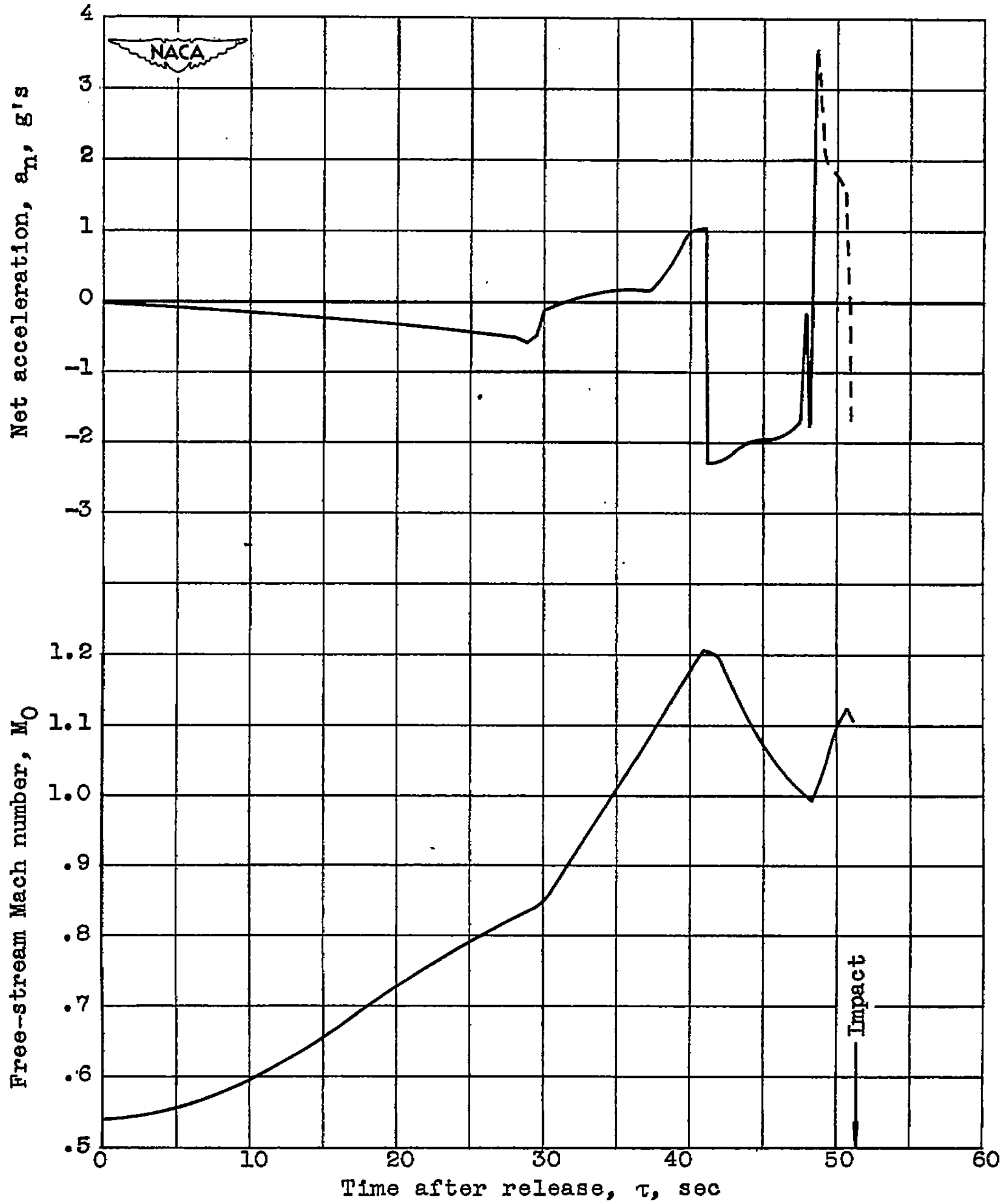
(d) Combustion-chamber-inlet variables.

Figure 8. - Continued. Time history of flight data and performance of ram-jet unit 16-D-3.



(e) Performance variables.

Figure 8. - Concluded. Time history of flight data and performance of ram-jet unit 16-D-3.



(a) Resultant flight conditions.

Figure 9. - Time history of flight data and performance of ram-jet unit 16-D-4.

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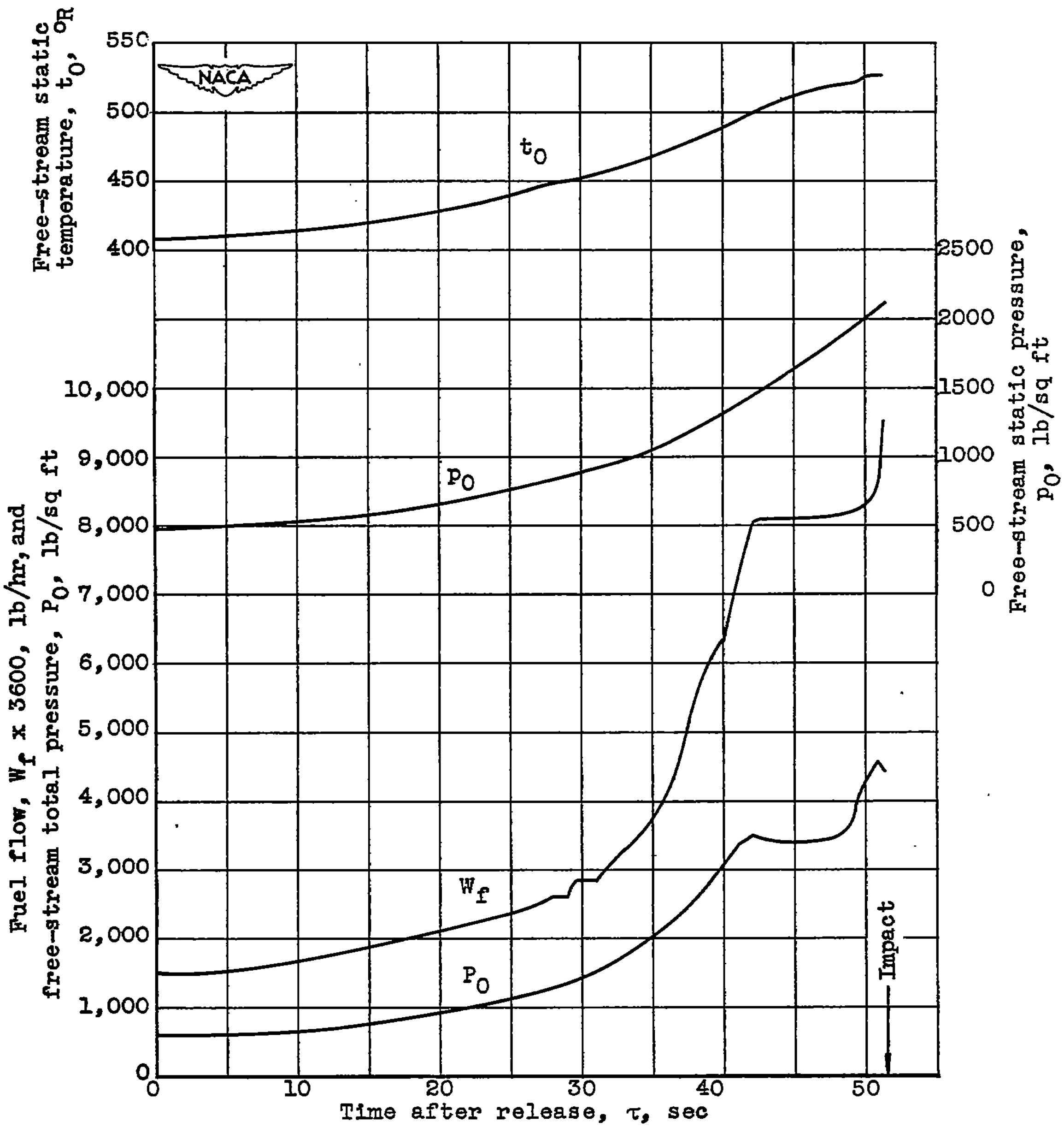

(b) Independent test variables.

Figure 9. - Continued. Time history of flight data and performance of ram-jet unit 16-D-4.

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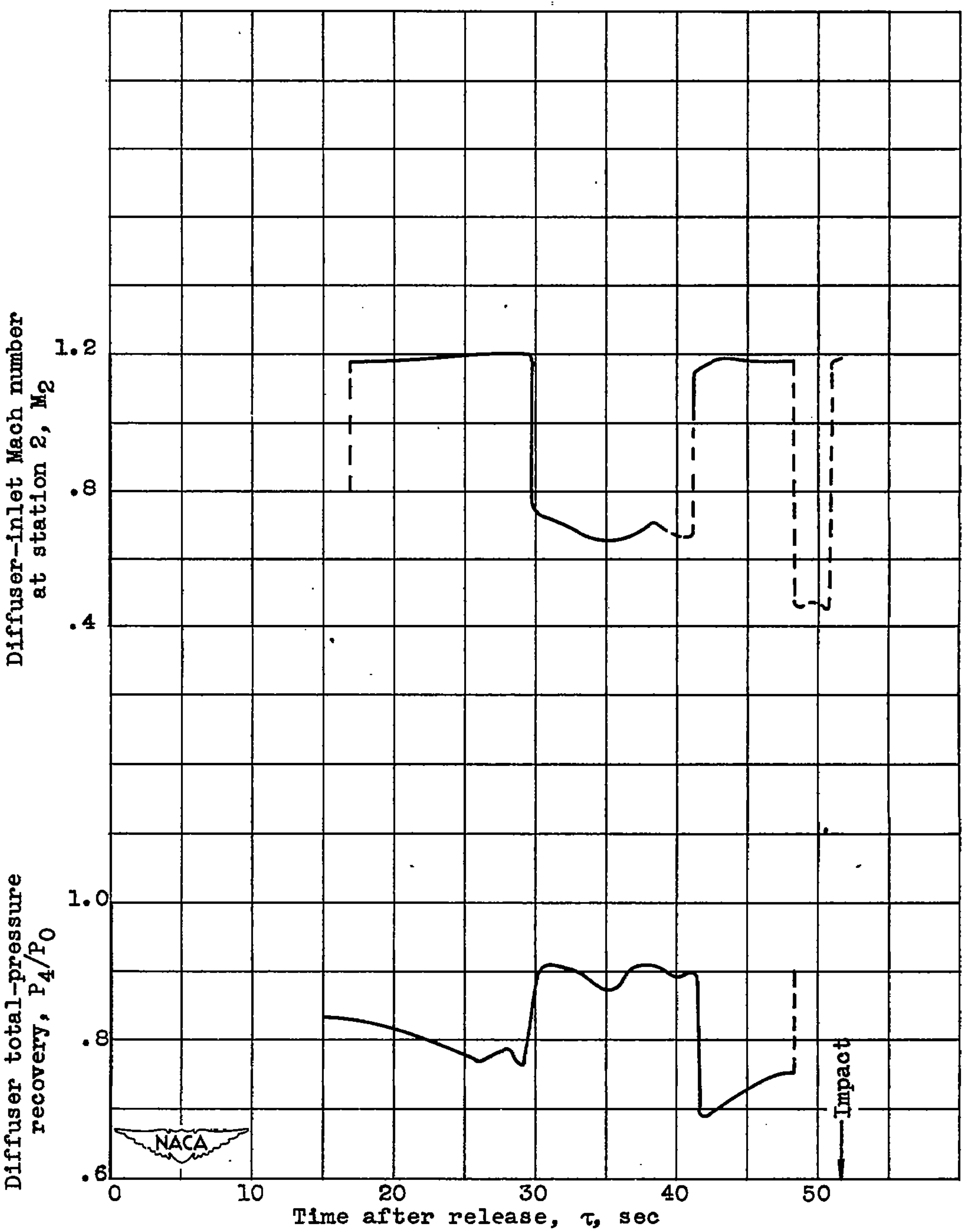

(c) Diffuser variables.

Figure 9. - Continued. Time history of flight data and performance of ram-jet unit 16-D-4.

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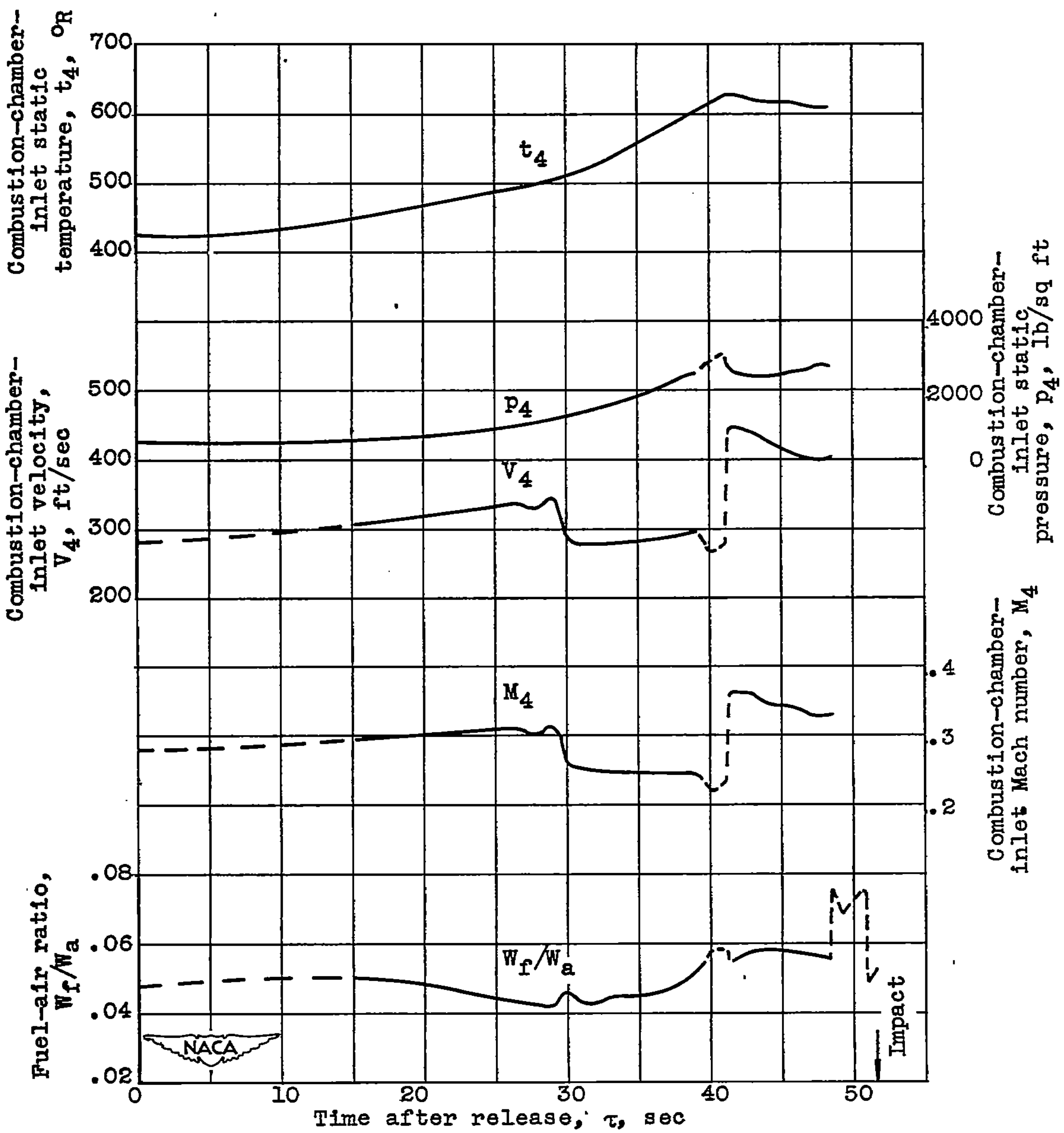

(d) Combustion-chamber-inlet variables.

Figure 9. - Continued. Time history of flight data and performance of ram-jet unit 16-D-4.

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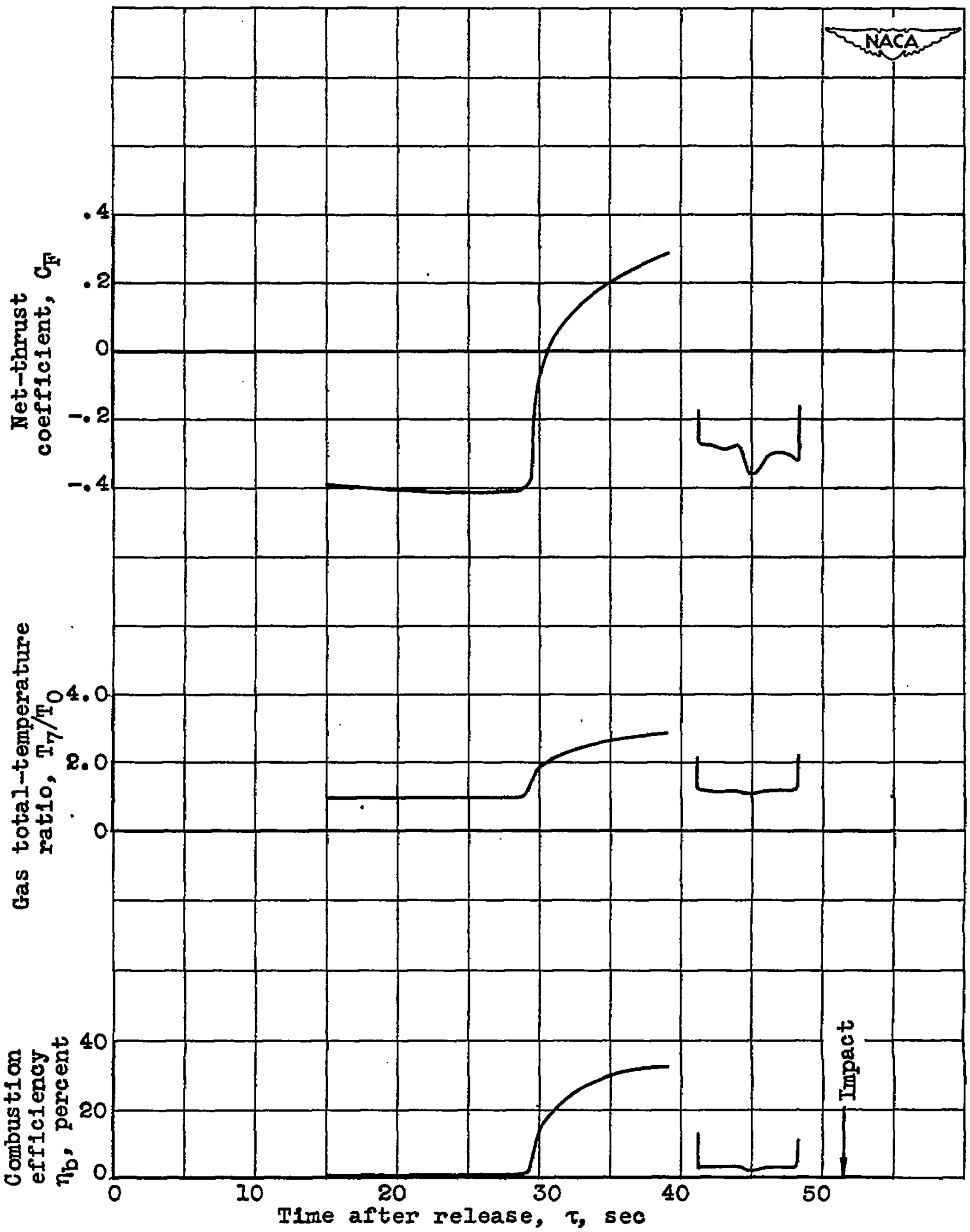


(e) Performance variables.

Figure 9. - Concluded. Time history of flight data and performance of ram-jet unit 16-D-4.

1294

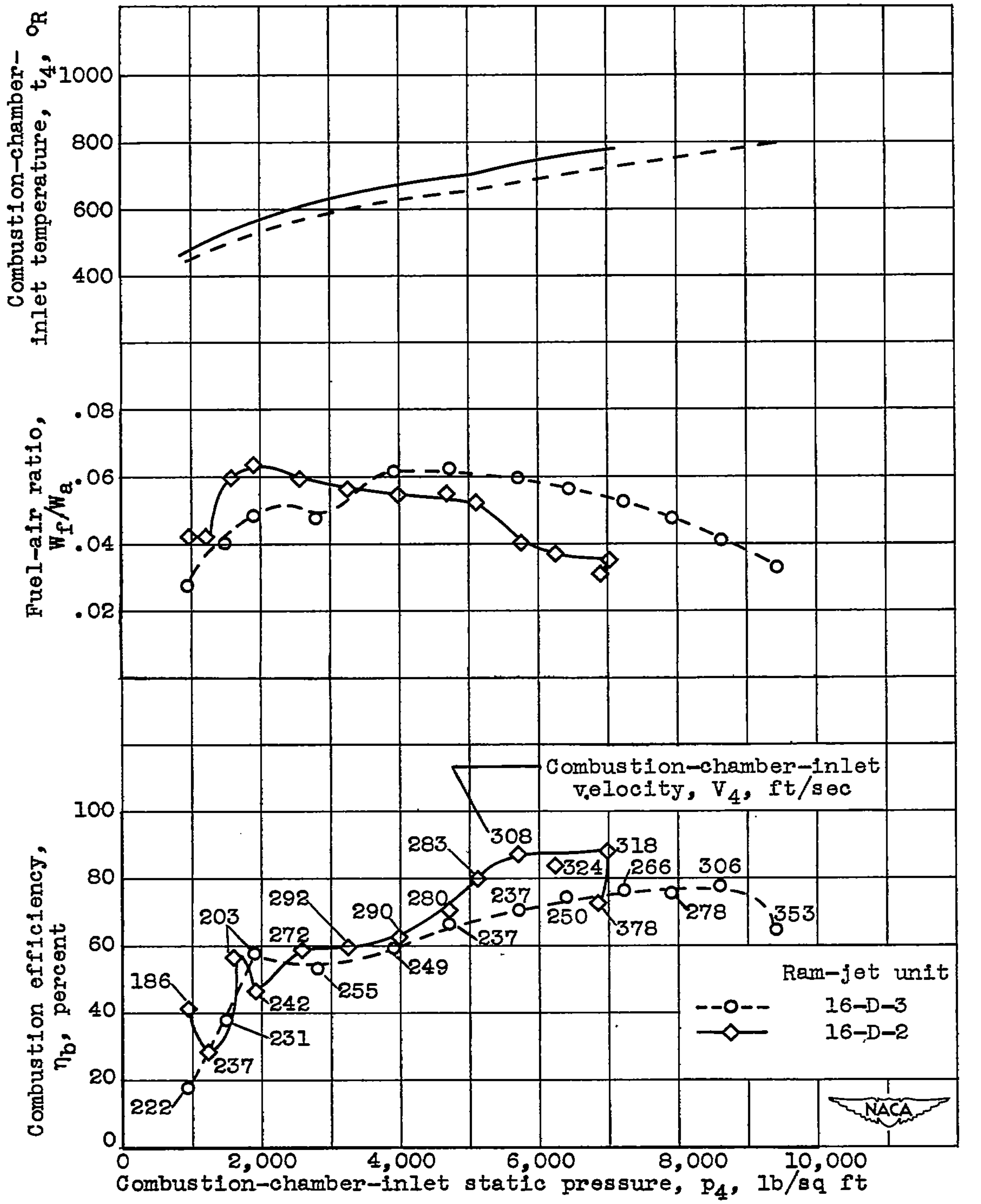
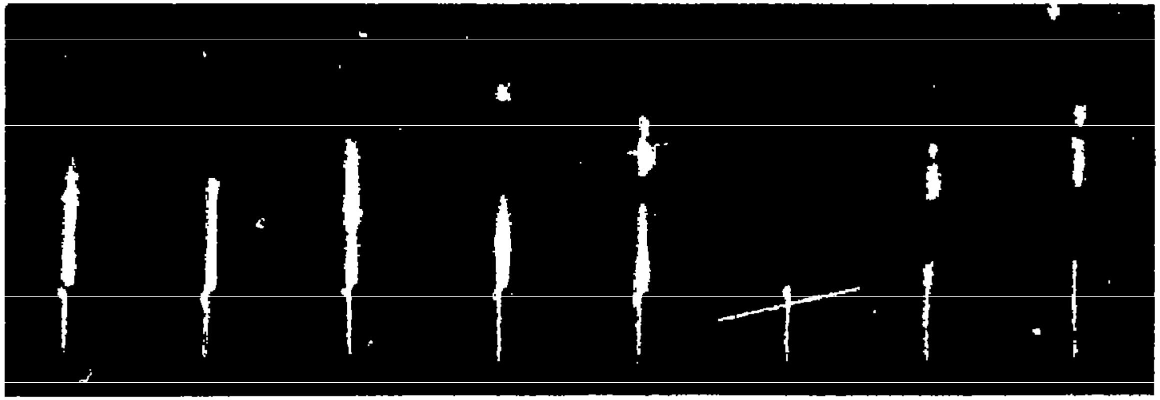
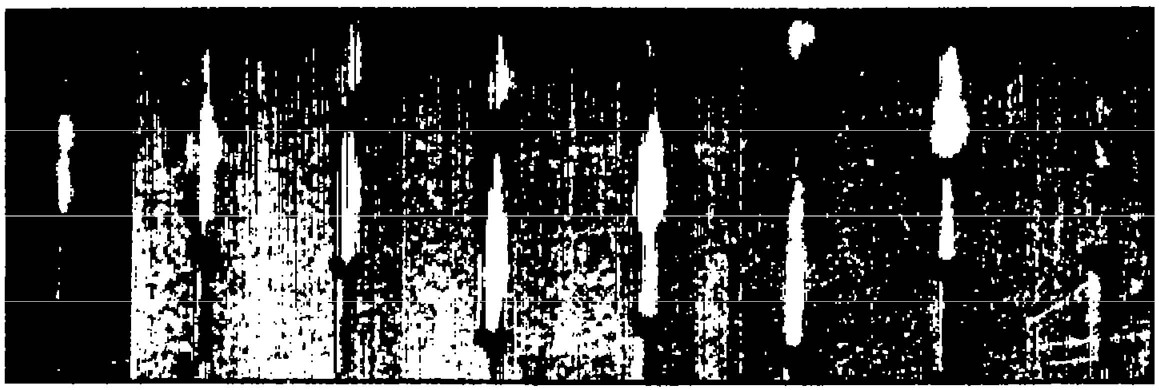


Figure 10. - Combustion-chamber variables as function of combustion-chamber-inlet static pressure.



Time, sec	39.4	39.8	40.2	40.6	40.9	41.1	43.6	46.2
Mach number, M_0	1.156	1.17	1.182	1.195	1.208	1.206	1.125	1.038
Fuel-air ratio	0.053	.057	.058*	.058*	.058*	.054	.058	.057



Time, sec	47.2	48.2	48.3	48.4	48.6	49.0	50.5	50.8
Mach number, M_0	1.011	.996	.996	.997	1.003	1.029	1.117	1.114
Fuel-air ratio	.057	.055	.075*	.075*	.075*	.068*	.075*	.049

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Figure 11. - Photographic record of variations in combustion process occurring during flight of ram-jet unit 16-D-4. (Asterisk denotes average value determined from vibratory air-flow data).

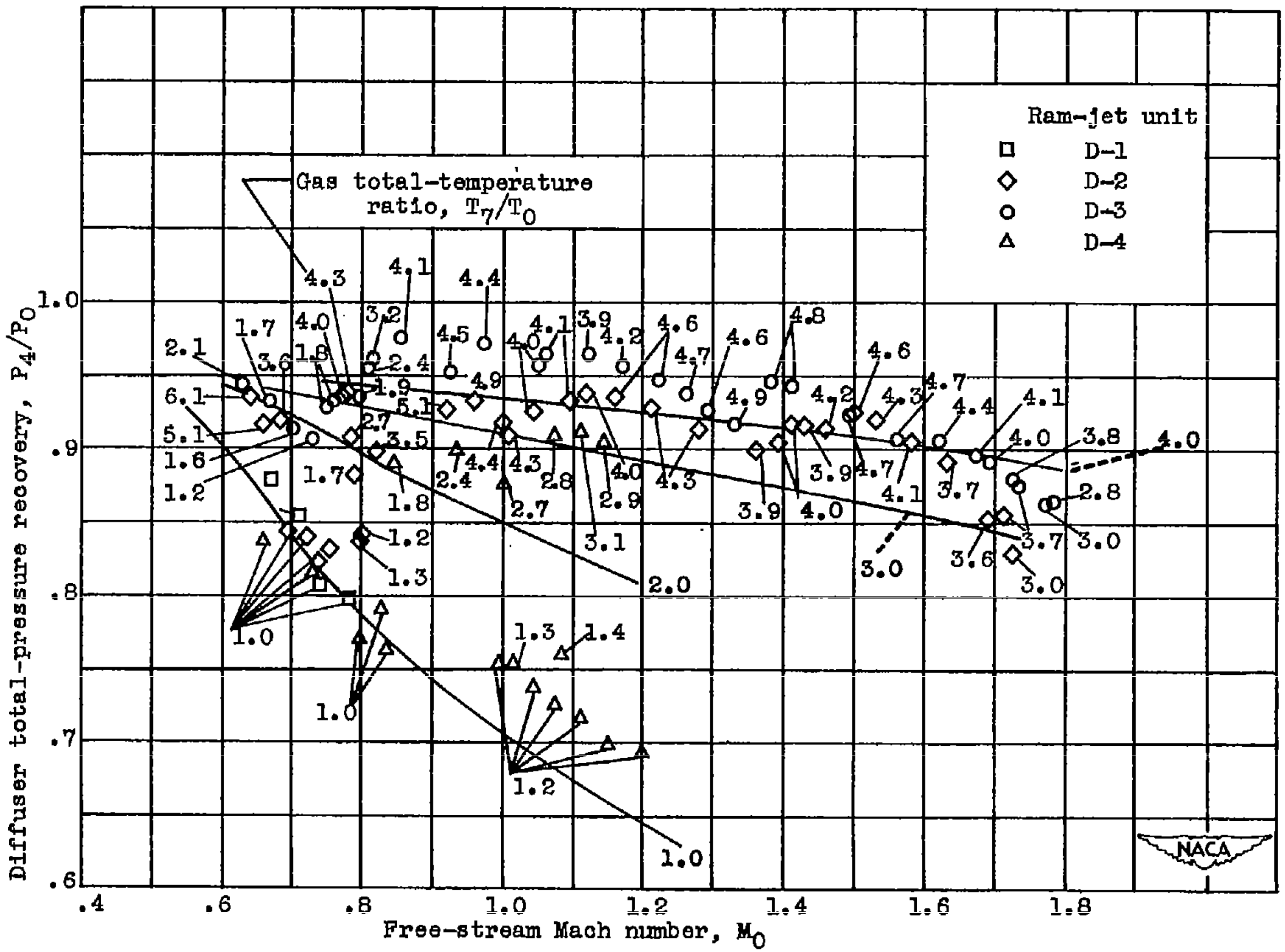

Figure 12. - Diffuser total-pressure recovery as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-D-1, 16-D-2, 16-D-3, and 16-D-4.

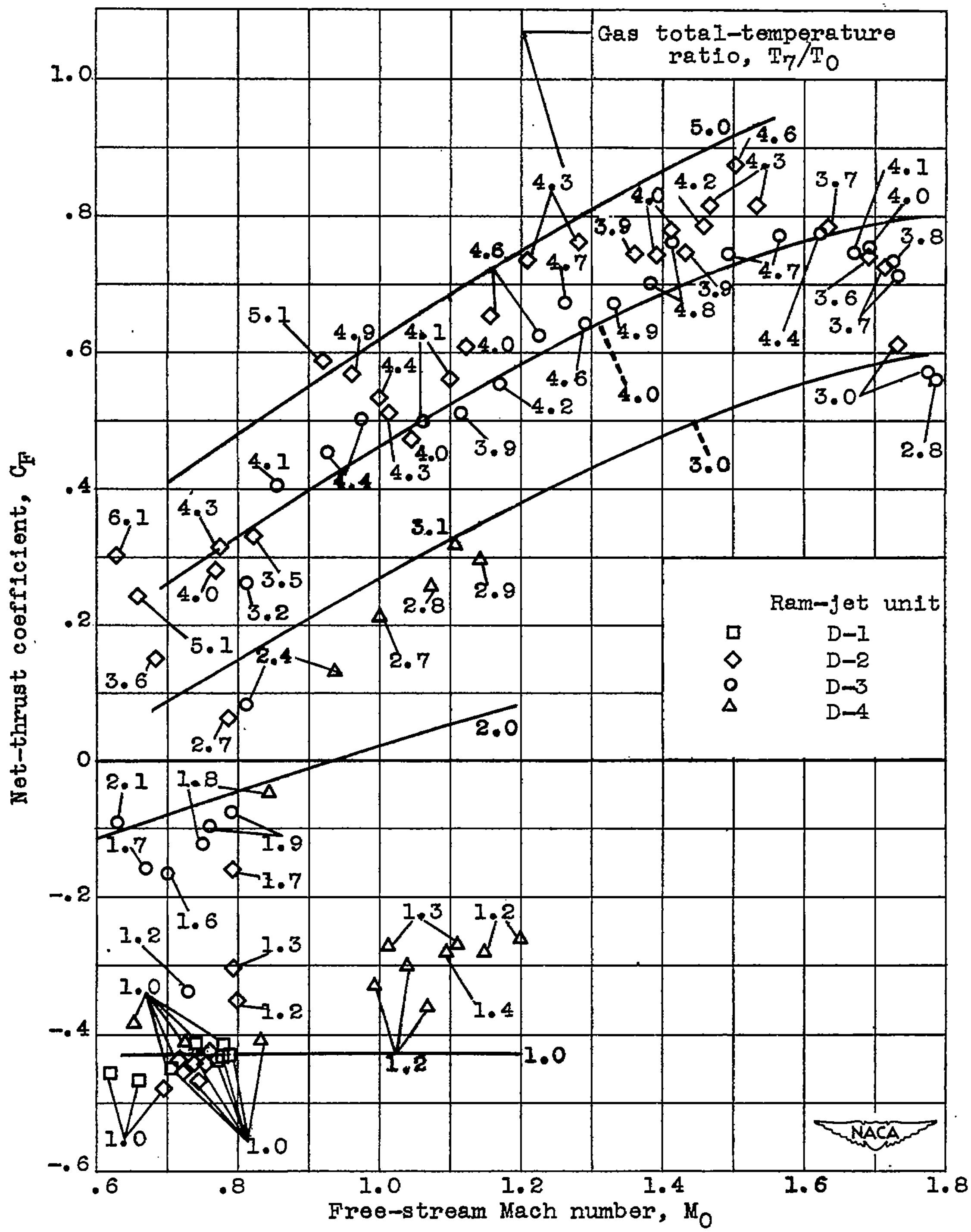

Figure 13. - Net-thrust coefficient as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-D-1, 16-D-2, 16-D-3, and 16-D-4.

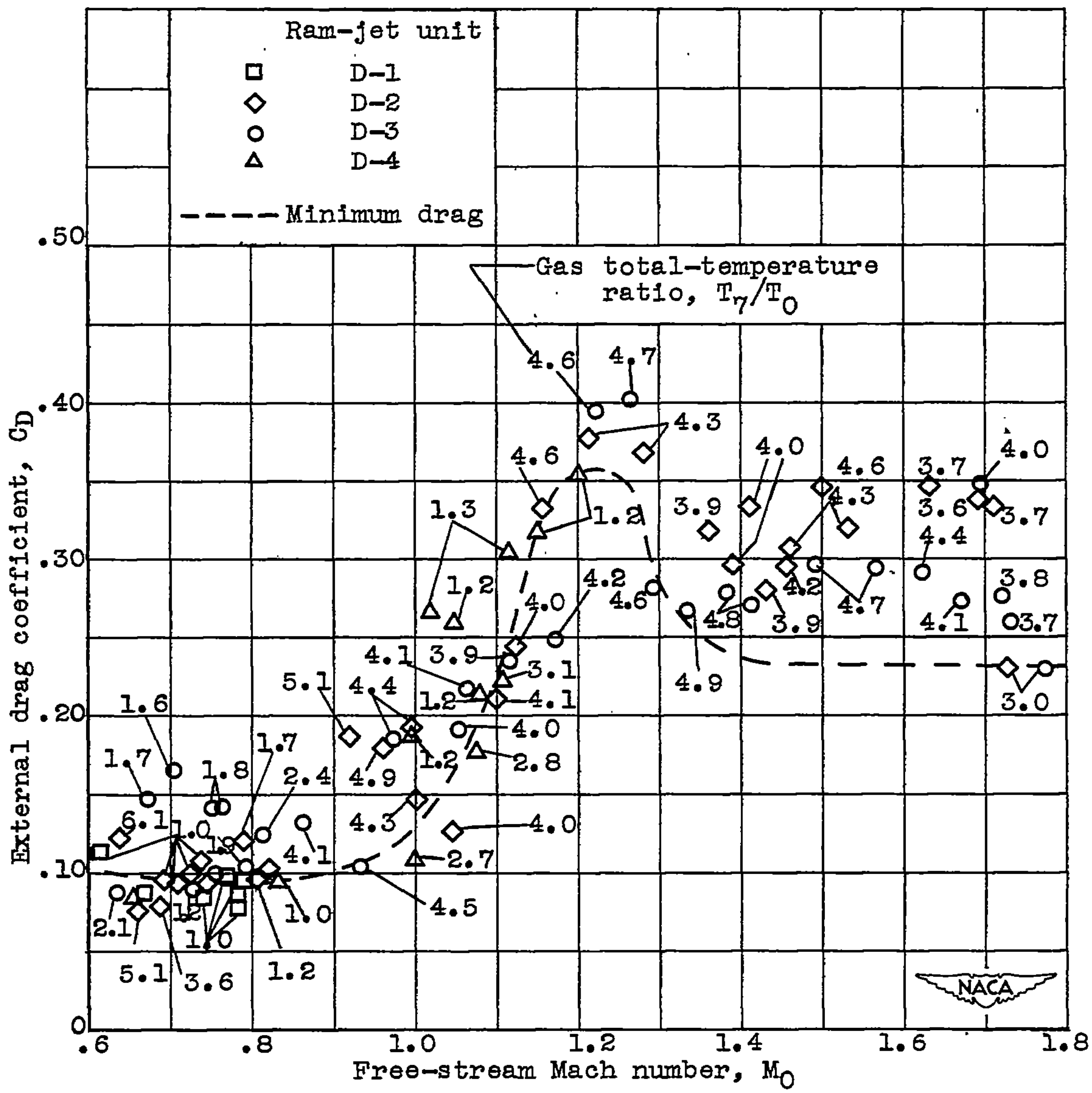

Figure 14. - External drag coefficient as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-D-1, 16-D-2, 16-D-3, and 16-D-4.